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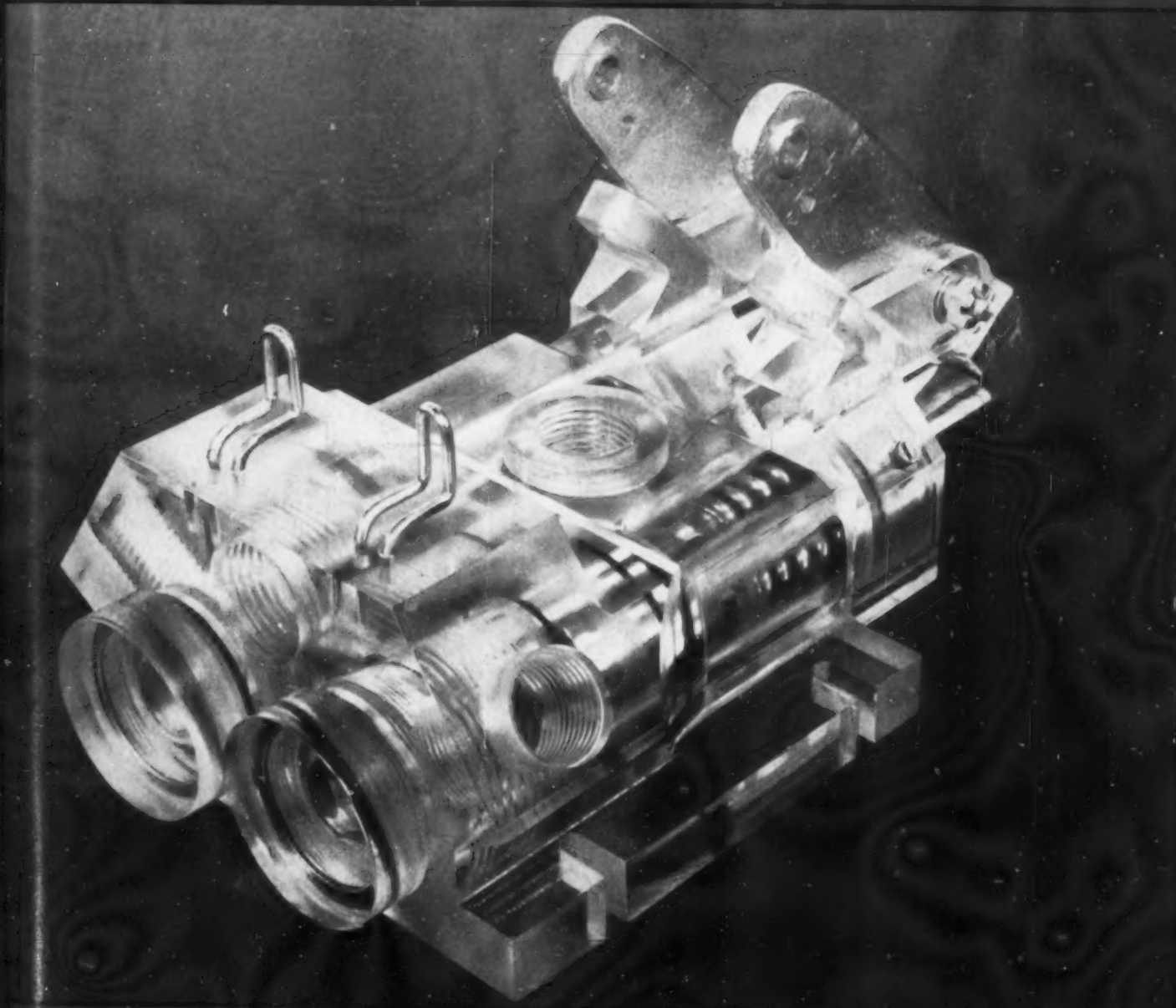

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Principles of Intricate Machines Visualized with the Aid of Plexiglas Models

(See Recent Applications of Physics)

JOURNAL OF APPLIED PHYSICS

Vol. 15, No. 12 DECEMBER, 1944

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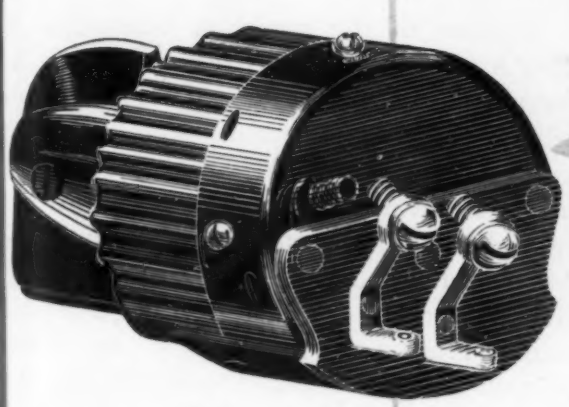

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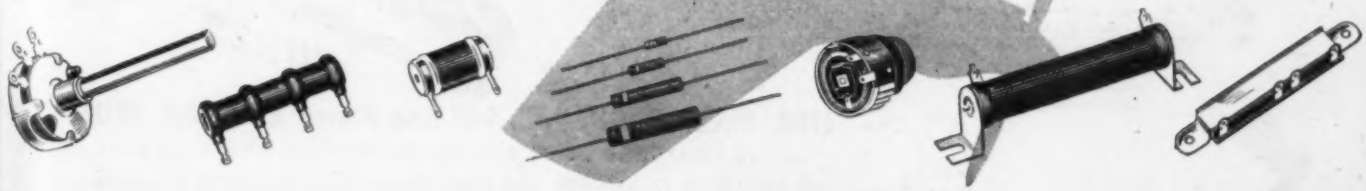

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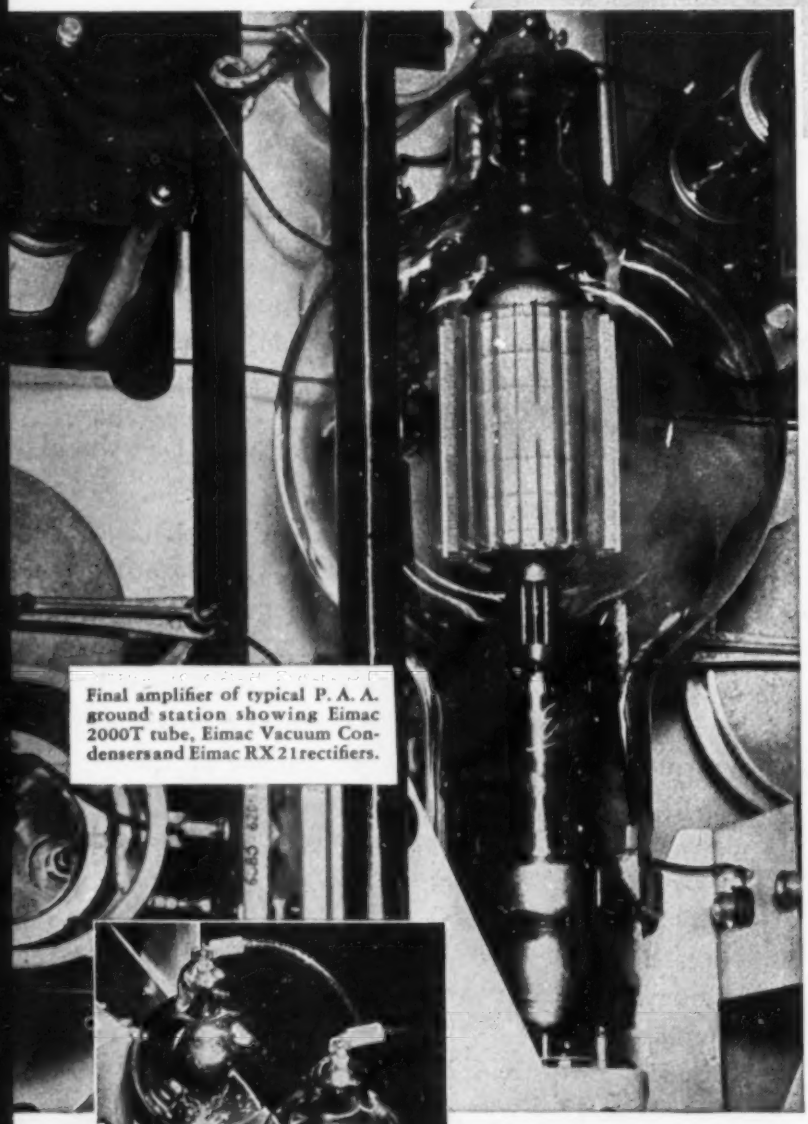

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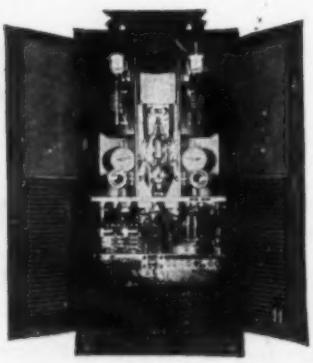

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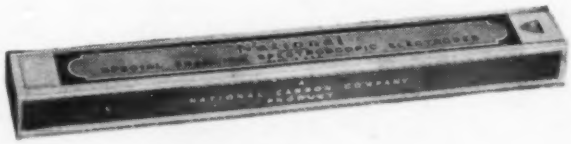

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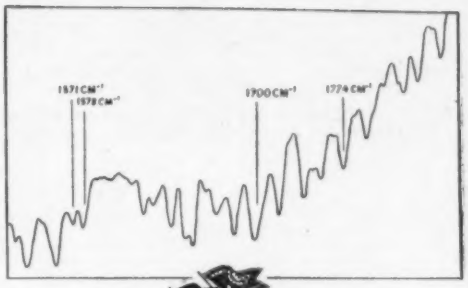

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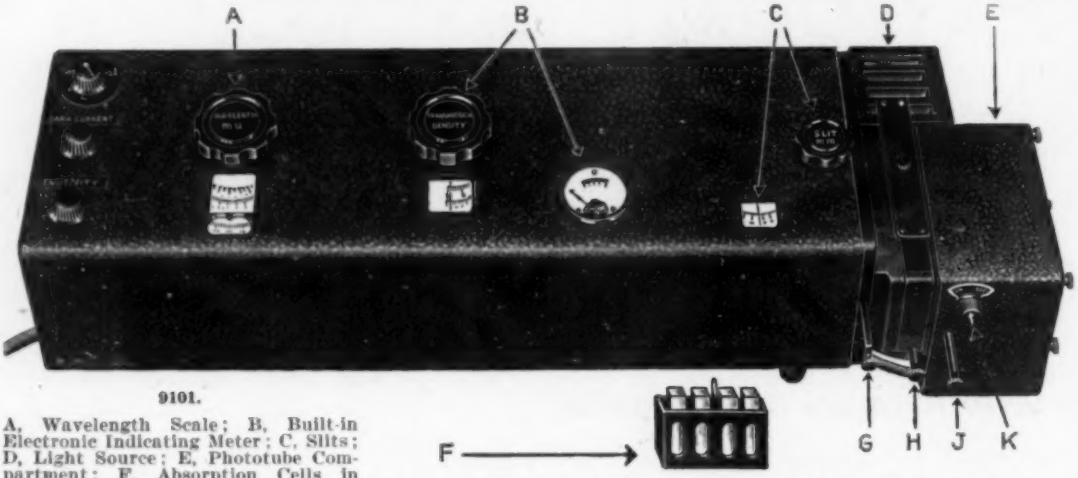

9101.

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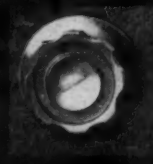

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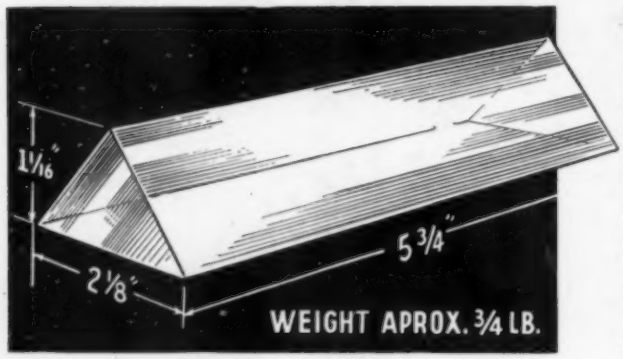

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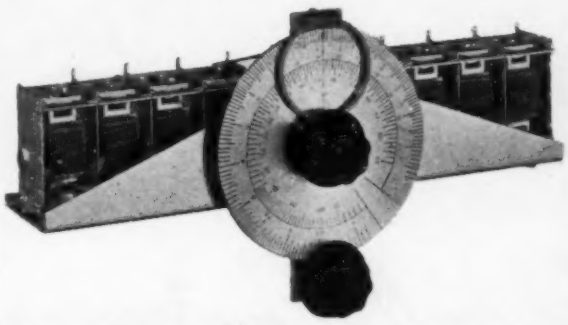

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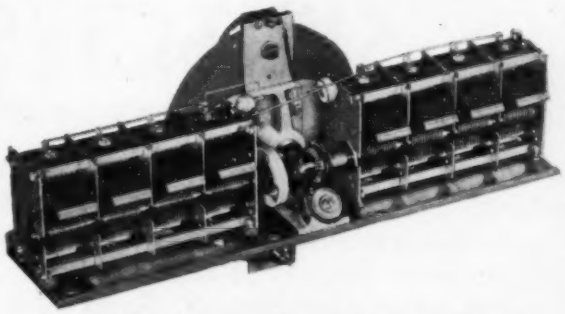

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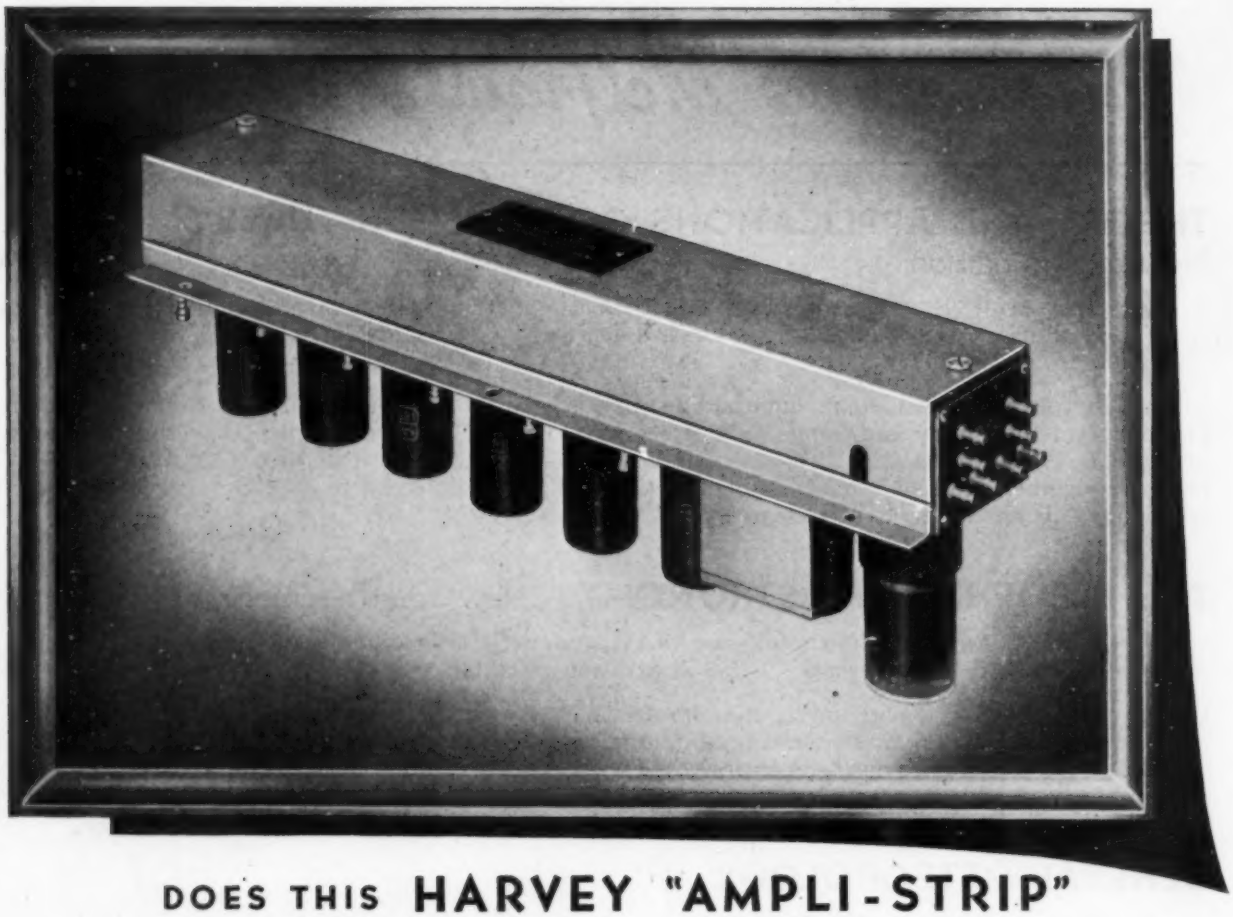

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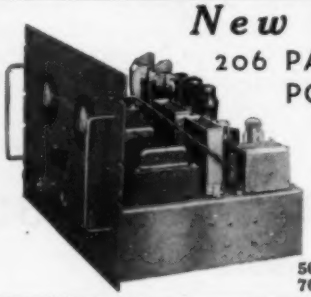

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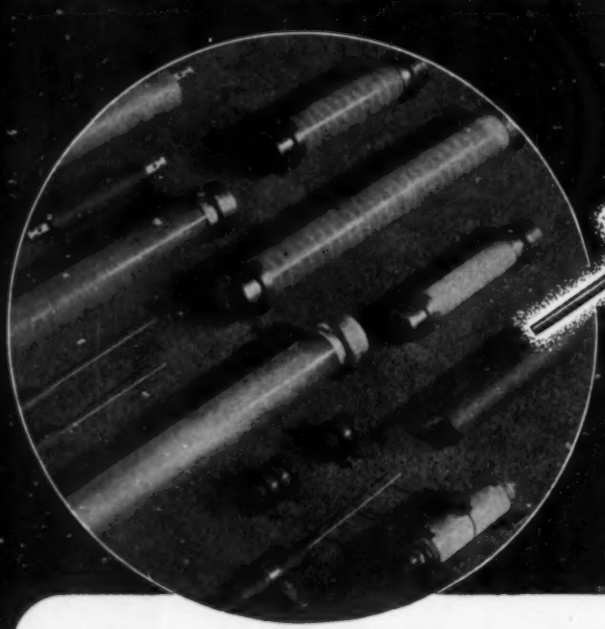

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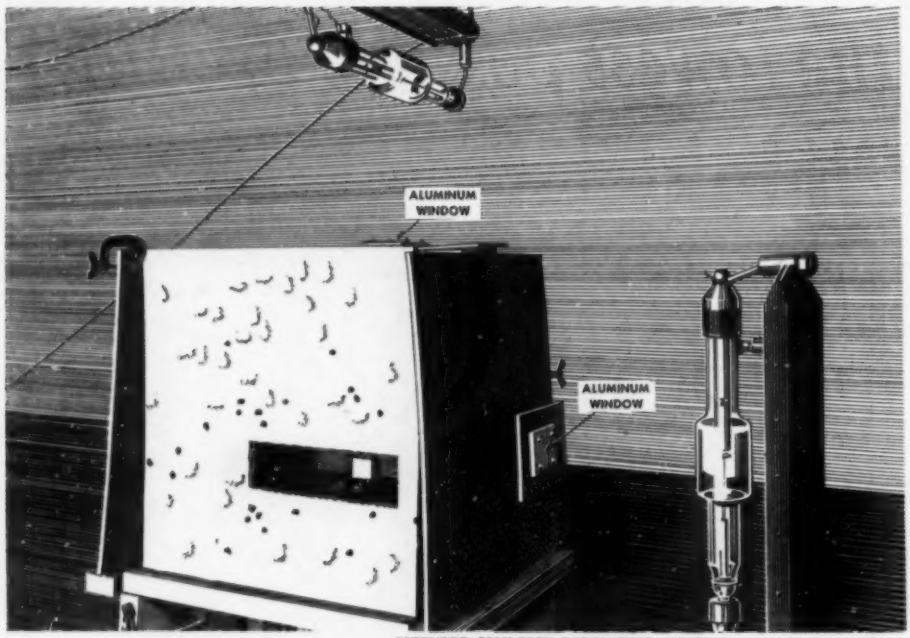

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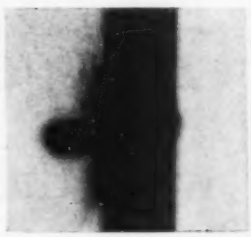

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Journal
of
Applied Physics

Volume 15, Number 12 December, 1944

Physics of the Solid State

STATEMENT PREPARED BY S. DUSHMAN, T. A. READ, F. SEITZ, W. SHOCKLEY, S. SIEGEL, AND R. SMOLUCHOWSKI

IN January, 1944 a group of six physicists sent a circular letter to about fifty members of the American Physical Society who were known to be interested primarily in metals or in the solid state in general, with the purpose of finding out their reaction to a proposed new division of the Society. According to the constitution, members of the Society may join a division and elect their officers. Since this procedure implies certain classification or subdivision of membership, an alternate suggestion was made to organize a committee which would take care of all the various tasks such as organizing symposia, etc., without introducing a separate "specialized" membership.

About sixty percent of the physicists have sent in their answers: half of them being in favor of a committee (as defined above), one third in favor of a regular division, and the rest opposed to any new action. With the kind cooperation of the secretary of the Society these results were presented to the Council at one of its meetings. The Council expressed itself essentially in favor of a regular division because this is provided for in the constitution and it appointed the original group of six physicists a committee to organize a symposium for one of the forthcoming meetings in the 1944–1945 season. A business session at this symposium should give ample opportunity for those interested in solids to express their opinion about the proposed steps.

There seems to be little doubt that the majority of those consulted is in favor of some form of cooperation among physicists interested in solids. However, there is a desire to avoid, as much as practical, too formal an organization. The question to be decided is whether to create a regular division with its own membership or to make all the necessary steps to authorize the existence of committees (or divisions) without subdividing the membership of the Society into specialized groups. The latter may necessitate a constitutional amendment. There are arguments in favor of both solutions: The formation of a regular division would follow the standard pattern of other divisions and is relatively simple; the formation of a committee (or a division without membership) avoids the dangers of overspecialization and stresses the unity of interest and of purpose of all physicists, but it encounters several difficulties.

One of the purposes of the Symposium on the Solid State at the January meeting of the American Physical Society is to provide an opportunity for those interested in solids to decide which is the most suitable form of organization and to elect the proper body to carry out a program of future activities.

The program of the Symposium includes invited papers on various topics in the field of pure and applied Physics of Solids. It is suggested that all those who wish to present regular (10 minutes) papers in that field would do so at the January meeting in New York.

Physical Aspects of Foaming in Steam Generation

HANS M. CASSEL

General Ceramics and Acatite Corporation, Keasbey, New Jersey

Vaporization of pure liquids is reviewed as a problem of heat transfer and the rate of vapor bubble creation. Applying an idea of Gibbs, the influence upon the activation energy of nucleus formation exerted by the contact angle at the vapor/liquid/solid phase boundaries as well as by the shape and size of submerged solids is quantitatively expressed by the reduction in the volume requirement of the nucleus. Possible effects of solutes in superheated liquids upon steam bubble creation and growth are discussed. The stabilization of foam in boiling electrolyte solutions is explained by the thermoelectric potential differences originating from the temperature gradient around growing bubbles. The effect of foam inhibiting agents (e.g., castor oil) is interpreted as a change in the rate of bubble creation caused by surface conditioning of heating elements and suspended particles.

SO-called "foaming" constitutes a major nuisance in stationary as well as in locomotive boiler operation. This phenomenon, although superficially resembling the foam formation of soap solutions, is basically different in nature from ordinary lathering or frothing. The production and stability of soap bubbles depend on the existence at the liquid/air interface of more or less condensed monolayers of oriented organic molecules. On the other hand, foaming of boiler waters may be caused merely by the presence of dissolved inorganic salts. Such solutions would not show approximately the same foam development with finely dispersed air injected as they do under boiling conditions.

Thus it appears that boiler-foaming is characteristic of steam generation from solutions, and in the following paragraphs an attempt will be made to trace the observed facts to their fundamental causes.

I. STEAM GENERATION FROM DISTILLED WATER

To understand the process of evaporation from solutions the simple vaporization of distilled water has to be analyzed first.

When a liquid mass is in thermal equilibrium with an adjacent mass of its vapor, there will be a kinetic exchange of molecules from one phase to the other so that the number of molecules condensed per unit time and area equals the number of evaporated molecules. It requires an excess of molecules passing in one direction over the number passing in the opposite direction to produce a noticeable evaporation or condensation. The factor which determines the direction of excess transfer is quite generally the temperature difference between the two phases, the molecules following a more or less abrupt drop in temperature set up at the phase boundary. Accordingly, the process of evaporation requires superheating of the liquid, and vice versa. If steam generation were restricted to the surface of the water level, we would have the complete theory of evaporation comprised in that simple statement.

However, the spectacular feature of boiling is the creation and the growth within the liquid, and particularly in the neighborhood of the heating surfaces, of numerous vapor bubbles which rise and burst after having reached the surface. If we postpone the discussion of the bubble origin at this instant, it is nevertheless obvious that the growth of a bubble is subject to the same general law as any evaporation; i.e., there must be a temperature gradient around the expanding bubble, and any increase of the bubble volume depends on a superheating of the surrounding liquid in regard to the vapor phase on top of the water level.

The importance of this requirement of bubble growth was fully recognized for the first time only 15 years ago in the work of Bosnjakovic,[1] who showed that superheating of the liquid provides the impulse to the heat transmission needed for evaporation. From this point of view the indispensable heat transfer through the heating surfaces to the boiling liquid appears as of secondary significance, which it certainly is when the heat transfer from the liquid to the vapor bubbles is the rate determining step in the whole process of ebulition.

[1] F. Bosnjakovic, *Technische Mechanik und Thermodynamik* (1930), Vol. I, p. 358.

Since the growth of a bubble implies an increase of surface in addition to that of volume the surface tension of the liquid is a decisive factor. In order to be in equilibrium with the liquid under a pressure p_{ex}, the vapor pressure in the interior of the bubble p_{in} has to be larger by the quantity $2\sigma/r$, where σ is the surface tension and r the radius of the spherical bubble. Now, the vapor pressure of a concave liquid is smaller than that of a plane surface of the same liquid at the same temperature p_0 by an amount which is given by the equation of J. J. Thomson:

$$p_{in}=p_0 \exp(-2\sigma M/rDRT), \quad (1)$$

where M/D is the mole-volume of the liquid. The only means of satisfying these conditions is by superheating the liquid in regard to the external vapor phase. The temperature required can be determined if the vapor pressure as a function of temperature is known. This relation is given by the equation of Clausius-Clapeyron when integrated over a reasonable temperature range:

$$\log p_0=\log p_{ex}+L(T-T_0)/RTT_0, \quad (2)$$

where L designates the molal heat of evaporation, and where it is assumed that the ideal gas law holds for the vapor phase. By eliminating p_0 we obtain the equation:

$$p_{ex}+2\sigma/r=p_{eq}\exp\left(\frac{L(T-T_0)}{RTT_0}-\frac{2\sigma M}{rDRT}\right), \quad (3)$$

which represents the correlation of the temperature of superheating and the size of the bubble in equilibrium with the liquid at that temperature. In developing the exponential and neglecting all but the first term we may write as a second approximation:

$$2\sigma/rp_{ex}=\frac{L(T-T_0)}{RTT_0}-\frac{2\sigma M}{rRTD}. \quad (4)$$

It is informative to exemplify this by a few instances: The excess temperature necessary for the existence of a bubble of radius 0.001 cm in water boiling under atmospheric pressure is 0.32°C, and under a pressure of 10 atmos. (200 lb./sq. in.) at 195°C only about 0.03°C. In applying the formula it will be noticed that the Thomson term $2\sigma/rRTD$, caused by the great value of R, plays only the rolé of a minor correction except when r approaches the dimensions of the water molecule ($r=1.6\times10^{-8}$ cm).

The preceding considerations refer to the equilibrium of a bubble within a superheated liquid. It is, however, important to realize that this equilibrium is unstable. Any smaller bubble than that defined by the critical radius, its internal pressure being insufficient to overcome the capillary pressure $2\sigma/r$, is condemned to collapse, whereas with the least excess in size it would tend to increase as far as circumstances permit.

Since the creation of a new bubble implies a start from molecular dimensions it may appear as if an unbelievably high local superheating would be necessary to make such an event possible. Indeed, on the grounds of classical thermodynamics this phenomenon would be absolutely unintelligible.

In the work of M. v. Smoluchowski[2] it was first realized as a consequence of the kinetic theory of matter that local fluctuations of density (pressure) and temperature do always occur within apparently homogeneous liquids. On the same basis, heterophase fluctuations must be expected within a liquid whose state is close to a transition point,[3] e.g., the formation of vapor bubbles in the neighborhood of the boiling point. In other words, such a liquid has to be considered as an emulsion within which bubbles of all sizes are dispersed according to a statistical distribution.

Of all possible bubbles we are here only interested in those which have reached the forementioned critical diameter and which have the greatest chance of contributing to the process of boiling. With M. Volmer[4] who was the first to approach the kinetics of phase formation from this point of view, we call these bubbles "nuclei." Providing that care is taken to keep the "emulsion" in a stationary state by supplying heat and feeding liquid, there will be a stationary number of "nuclei" in the liquid. According to the laws of statistical mechanics[5] this number can be represented by an expression: $B=C\exp(-W/kT)$, where C is a relatively slowly varying function of the temperature. W, the work required to form (by a reversible process) the vapor bubble of critical size, may be called the activation energy of the process. As J. Willard Gibbs[6] has shown,

[2] M. v. Smoluchowski, Ann. d. Physik **25**, 205 (1908).
[3] J. Frenkel, J. Chem. Phys. **7**, 538 (1939).
[4] M. Volmer, Zeits. f. Elektrochemie **35**, 555 (1929).
[5] R. C. Tolman, *Statistical Mechanics* (Reinhold Publishing Corporation, New York, 1927), p. 320.
[6] J. Willard Gibbs, *Collected Works* (Longmans, Green and Company, New York, 1928), Vol. I, p. 257.

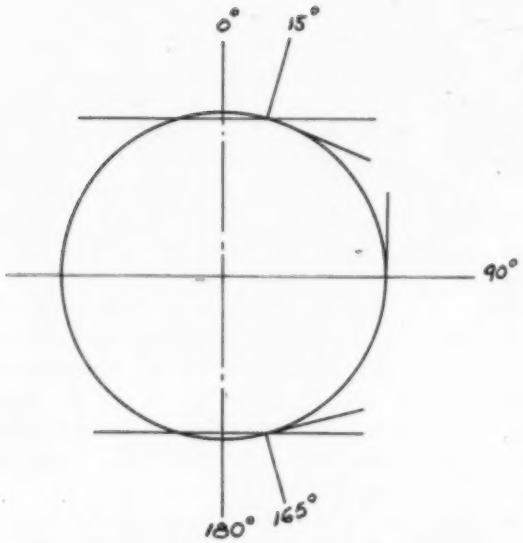

FIG. 1. Reduction of steam nucleus volume with decreasing contact angle. The segments underneath the straight lines represent volumes replaced by solid phases.

the free energy of phase formation can always be represented as well by one-third of the work required to form the nucleus surface:

$$W=\tfrac{1}{3}\sigma\cdot s \tag{5}$$

as by one-half of the work required to form the nucleus volume:

$$W=\tfrac{1}{2}V(P_{\text{in}}-P_{\text{ex}}). \tag{5a}$$

If we now consider the mean lifetime of the nucleus τ, we arrive at an expression for the rate of nucleus formation, in the present example for the number of vapor bubbles developed per cc, per sec.:

$$-\frac{dB}{dt}=\frac{C}{2\tau}\exp\left(-W/kT\right) \tag{6}$$

which can be checked experimentally.

For this purpose it is most helpful to eliminate the radius of the globular mass by means of the approximation $2\sigma/r_0=P_0-P_{\text{ex}}$ so that we can write:

$$W=16\pi\sigma^3/3k(P_0-P_{\text{ex}})^2. \tag{7}$$

Since the interfacial tension decreases steadily while the denominator increases with rising temperature, the exponential in (6) must be expected to increase rapidly within the narrow temperature range where the rate of bubble formation becomes observable.

It is well known that pure liquids, void of suspended matter, can be subjected to very high superheating without boiling. Thus, Faraday[7] found it possible to heat water under atmospheric pressure up to 132°C before it exploded. K. L. Wismer,[8] in a very thorough study of the phenomenon, found that carefully purified ethyl ether (b.p. 34.5°C) can be heated up to 143°C before it explodes when the pressure is reduced to 1 atmos.

On the basis of Wismer's data W. Doering[9] has estimated the order of magnitude of the factor $C/2\tau$ in Eq. (6) to be 10^{29}.

It is safe to conclude that spontaneous bubble formation never occurs in boiler waters and that boiling would be a most dangerous proposition if it were not for the catalytic effects of suspended particles and heating surfaces.

Obviously the formation of a new vapor/solid interface may require less work than the formation of the vapor/liquid surface in the case that the solid surface is not well wettable by the liquid. It has become customary to call such a surface hydrophobic if the liquid is water. A quantitative measure for this behavior is the angle of contact at the three-phase boundary solid/steam/water.

To visualize the effect of the contact angle upon the rate of bubble formation we take advantage of Gibbs' definition of the free energy W as half the product of pressure difference and nucleus volume.

The pressure difference $P_{\text{in}}-P_{\text{ex}}$, being fixed by the operating conditions (T and P_{ex}), determines the radius of the critical bubble, no matter what the value of the contact angle. But the volume of the sessile bubble attached to the solid surface will be the smaller as the greater a part of the full sphere is cut off by the solid body. For instance, if the contact angle is 90°, the nucleus forms a half-sphere and, accordingly, only half of the work required to form it in absence of the solid is necessary. Figure 1 may serve to illustrate these very simple relations. It will be noticed that the bubble volume approaches zero as the contact angle reaches this limit and, on the other hand, the volume increases to that of the full sphere when the contact angle becomes 180° for a perfectly wettable or hydrophilic solid surface. In the

[7] M. Faraday, Royal Institution (June, 1850).
[8] K. L. Wismer, J. Phys. Chem. **26**, 301 (1922).
[9] W. Doering, Zeits. f. physik. Chemie **B36**, 371 (1937); **B38**, 292 (1938).

latter case, the work of bubble formation remains the same as in absence of the solid, whereas, for the perfectly hydrophobic surface, when the quantity $W=0$ a minimum of superheating would be sufficient to keep the water boiling, the rate of bubble formation would be at its maximum.

The preceding considerations concerned the ideal case of perfectly smooth, plane surfaces; it can be anticipated, however, that the natural or artificial roughness of heating surfaces may substantially change the conditions. M. Jakob[10] and his co-workers, in their broad investigation of this field, have definitely established the very pronounced differences in the effects of smoothness and roughness upon the type of steam bubbles formed and upon the temperature distribution in the boiling waters. There can be no doubt that greater roughness facilitates evaporation as is proved by the lowering of the mean temperature of superheating.

The question naturally arises whether the protruding or the concave parts of the roughened surface are responsible for the observed change. According to the theoretical point of view as here presented, this reduces to the question: Will a greater part of the nucleus volume be cut off by a protrusion or by a cavity? In the special case of the alternative between a conical tip and a conical dip, as illustrated in Fig. 2 for a contact angle of 90°, the larger share cut off by the dip will be easily noticed. Whatever the contact angle and the shape of the surface irregularity may be, it is evident that cracks and cavities are likely to contribute the most to reducing the activation energy of nucleus formation.

Of course, this argument can also be applied in judging about the efficiency of particles of suspended matter. Even with perfectly hydrophobic particles little can be expected unless the volume of the particles is large enough to displace a major part of the nucleus volume. Therefore, in general, the contact effect of larger particles must be superior to that of smaller ones.

II. STEAM GENERATION FROM SOLUTIONS

There is no foam development in distilled water; apparently, once formed, bubbles do outgrow to the largest possible size or coalesce with colliding neighbors. By some reasons, conditions are different in solutions. In surveying the known facts one arrives unfailingly at the conclusion that the tendency towards foaming increases as the concentration of dissolved matter rises. This is very strikingly demonstrated by the success of "blowing-down" in locomotive operation which belongs to one of the most strictly observed regulations of railroad engineering.

In feeding the boiler continually with salt containing water, the concentration of the solution, caused by the evaporation of the water, increases steadily. This may or may not result in the precipitation of supersaturated components. However, in order to keep the concentration below a certain level which is considered as being critical to foam production, water is withdrawn from the boiler either continuously or in periodic intervals. For instance, if a tenfold

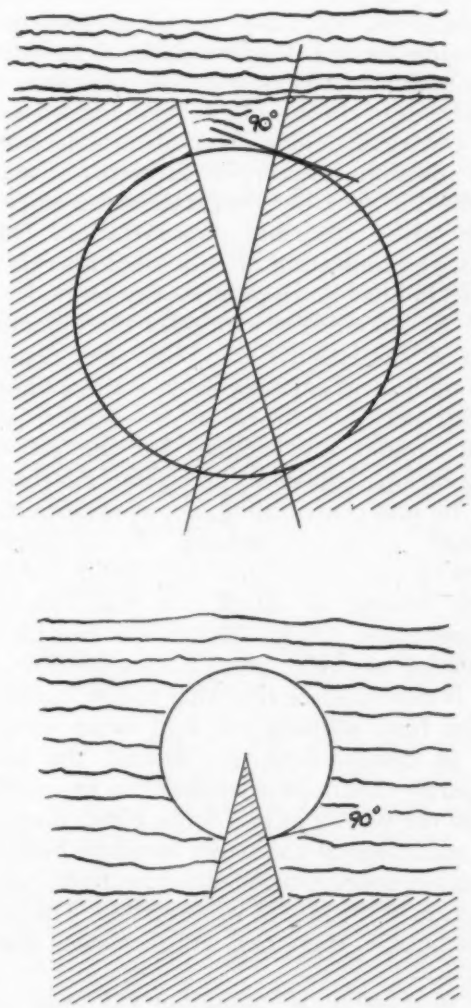

FIG. 2. (a) Nucleus volume reduction owing to dip. The wavy lines indicate water, the shaded part solid, and the unshaded part steam. (b) Tip.

[10] M. Jakob, Mech. Eng. (Oct. and Nov. 1936).

increase in the concentration of the feed water shall not be surpassed, one-tenth of the water has to be blown down. Needless to say, this is a serious waste of energy.

The question as to why the presence of electrolyte in the water under otherwise unchanged conditions enhances the formation and stabilization of more numerous bubbles than occur in less concentrated solutions has not yet been satisfactorily answered.

C. W. Foulk[11] has advanced the idea that the difference is caused by an increase of the stability of the bubbles, which in a way similar to the stabilization of emulsions, are prevented from coalescence, presumably by the action of electric double layers surrounding the individual bubbles. This point certainly deserves attention. However, to the present reviewer it appears that the origin of the postulated electric forces cannot be the same as in colloidal solutions. In the latter case stability is caused by the existence at the interfaces of the so-called Z potential. However, the electrical double layer always decreases on the addition of more electrolyte; it may be reversed in sign, but nevertheless becomes negligible with increasing concentration. On this basis, the limitation of concentrations as maintained in blow-down practice cannot be justified.

N. K. Adam[12] has expressed the opinion that the stabilization of the bubbles may depend on the building up of insoluble crystalline films such as carbonates, hydroxides, or sulfates, precipitated around the bubbles by the process of evaporation. However, precipitation, though it may be one contributing factor, is certainly not the only cause of foaming. W. B. Leaf[13] has observed very pronounced foaming in the atmospheric boiling of alkali salt solutions whose concentration (26 g/1000 cc) is too far from saturation to render precipitation possible.

It is nevertheless true that steam bubble formation from solution will lead to an accumulation of dissolved matter around the bubble. Evidently this must contribute to the stabilization of the bubble in two ways. First, there must be a reduction of the vapor pressure because of the higher concentration which, in turn, causes a reduction of the rate of vaporization. The growth of the bubble, therefore, will be slowed down in an earlier stage, i.e., at a smaller size than in absence of the solute. With diminished cooling of the bubble neighborhood, superheating will spread to its closer vicinity and, in the presence of sufficiently effective suspended particles, more numerous and more densely distributed bubbles can originate and grow than in pure water, even in the presence of the same kind of suspended matter. Second, the existence of a concentration gradient between the surface of the bubble and the interior of the solution implies the building up of an electrical potential difference whose magnitude depends on the transfer numbers and activities of the electrolyte.

No doubt, the picture as outlined does not yet give the complete story. Two more factors have to be considered: first, diffusion which counteracts the described effect; second, the Ludwig-Soret phenomenon which definitely serves to promote the described effects.

The birth of a bubble, comprising its growth from nuclear to visible dimensions—radius r_0—is generally very fast; as M. Jakob put it, "an explosion in microscopic scale." The electrolyte previously contained in the volume $4\pi r_0^3 q/3$ of water (q designates the ratio of the densities of steam and water) must then have been dumped into a spherical shell of thickness d and volume $4\pi r_0^2 d$, thus increasing the concentration of this layer from c to $c+cr_0q/3d$. Although the diffusion coefficient D of electrolytes are measured by cm^2 per day, the decay of the excess concentration is surprisingly rapid. From the elementary equation of the diffusion theory which represents the case:

$$c_{\text{excess}} = \frac{cr_0q}{2\sqrt{\pi Dt}} \exp\left(-r_0^2/4Dt\right),$$

one has to conclude that this is caused by the smallness of the factors q (in the order of 10^{-4}) and r_0 (in the order of 10^{-3}), with D in the order of 10^{-4} at the temperatures obtaining.

The effect under consideration, accordingly, can be responsible only for the early termination of the explosive phase in the development of the steam bubble, and therefore, as mentioned above for a higher degree of superheating and for the creation of more numerous smaller bubbles than originate in pure water. But, this effect does not account for the prevention of coalescence in the later phases of bubble life.

Owing to the velocity of the diffusion effect the bubble will continue to grow, though with a reduced rate, and consequently the temperature

[11] C. W. Foulk and K. Groves, Ind. Eng. Chem. **25**, 800 (1933).
[12] N. K. Adam, *Physics and Chemistry of Surfaces* (Oxford University Press, 1938), p. 146.
[13] W. B. Leaf, Am. Railway Eng. Assn. **45** (May, 1944).

gradient around the bubble will persist. Now it is well known that in a solution, different sections of which are kept at different temperatures, the greater kinetic energy of the warmer parts forces an excess of solute to migrate towards the cooler ones. In electrolyte solutions this produces the above-mentioned electric potential differences which since van't Hoff[14] discussed them first have been repeatedly investigated under the headline "electrolytic thermocouples."[15]

Not before the steam bubbles cease growing in the top layers of a foam column will the repelling electromotive forces sufficiently diminish to allow the coalescence of adjacent water films. From the standpoint of Foulk's theory, if it is presumed to give an explanation for the stability of steam bubbles, their final collapse cannot at all be understood.

In closing this discussion it should be said that certain consequences of the theory here advanced have, so far, not yet been subjected to experimental checking. For instance, it should be expected that the tendency to foaming as measured by the height of the foam column obtained is proportional to the molar electrolyte concentration rather than to the weight of dissolved matter customarily used in water treatment calculations. Also, the correlation of foaming and the thermo-electrolytic potential differences characteristic of the solutions lacks definite confirmation.

III. MECHANISM OF FOAM INHIBITION

For years numerous attempts have been made to combat foam development in boiler operation by injection into the feed waters of certain organic compounds. Among these castor oil has found the most widely spread application. Castor oil which contains a high percentage of ricinoleic acid spreads easily on water. Therefore, its efficiency was sometimes attributed to the surface activity of that compound. The present theory does not leave any basis for this belief. To the contrary, since the accumulation of organic molecules in the surface layer of an expanding bubble necessarily reduces its permeability to water molecules,[16] the above-described effects of the electrolytes should be rather accentuated than diminished by capillary active substances.

In the opinion of the present reviewer the foam inhibiting agent does not work at the water/steam interface, supposedly facilitating the coalescence of bubbles, but at the heating surfaces and those of suspended particles. In other words, it appears that by properly conditioning these interfaces the number of bubble nuclei can be drastically reduced so that fewer but larger bubbles are formed, before coalescence could be of significance.

Postponing the discussion of the heating surfaces let us assume that in absence of the foam inhibitor there are in any unit volume of the liquid mass enough particles of proper interface condition to allow of bubble formation where and when the degree of superheating is sufficient. This will be quite regularly the case. There is always plenty of precipitated matter when hard feed waters have been given an alkaline treatment.

Supposing that the addition of anti-foam agent has rendered the surfaces of all suspended particles strongly hydrophilic; then, a too high degree of superheat would be required to develop on these particles steam bubbles so that those possibly observed must originate at the heating surfaces.

On the other hand, if the suspended particles are sufficiently hydrophobic the number of bubbles liberated on the slightest superheating will correspond to the number of particles. This may be of little consequence under moderate steam draw-off during which the particles will be removed from the interior to the cooler top layers of the water by a process of steam flotation. However, a very undesirable situation will arise, at least temporarily, from a sudden increase in the steam consumption with the concomitant sudden superheating of the whole liquid body. It is true that after an initial outburst of foaming, quiet boiling may soon be restored; but the first shock of foaming, particularly when frequently repeated, may be objectionable enough.

The behavior of the heating surfaces in absence of foam producing agents has been thoroughly studied in the work of M. Jakob and his coworkers. According to their observations three typical cases can be distinguished: (A) On unwetted surfaces, produced by a thin layer of mineral oil, the bubbles, while they grow rather large, are spreading over the heating surface until they finally break off; (B) the bubbles originate from a few active spots irregularly distributed over an apparently smooth surface which Jakob considers as being half-wettable;

[14] J. H. van't Hoff, Zeits. f. physik. Chemie **1**, 487 (1887).
[15] W. Nernst, *Theoretische Chemie* (1913), p. 801.
[16] I. Langmuir, J. Frank. Inst. **235**, 119 (1943).

the bubbles rise from the active spots closely following each other as in a row of pearls; (C) the surface has been fitted with square cavities 0.25 mm in length and distance. Here, apparently the whole surface is well wetted and it is hard to say whether the bubbles originate on the surface itself or in its immediate neighborhood. From a photograph reproduced in Jakob's paper one would gather that corresponding to the great number of cavities a dense cloud of bubbles originates from as many active centers.

In practical boiler operation the heating surfaces are generally coated with a scale of precipitated matter. Under atmospheric boiling and with moderate heat input the appearance of the bubbles resembles that of case (B). But on increasing the heat supply bubble formation assumes the features of case (C).

This in electrolytic solutions means foaming; and the question of what alterations may be expected from conditioning the heating surfaces shall be briefly discussed.

If the foam inhibitor modifies surfaces in a hydrophobic way conditions are similar to Jakob's case (A), i.e., only relatively few (but large) bubbles form; foaming would practically subside except for the temporary contributions of suspended particles as previously described. Unfortunately, there would be caused by a hydrophobic type of foam inhibitor another undesirable effect. This is, as Jakob has already emphasized, a reduction of the heat transfer through the heating surface. Although part of the energy will be immediately transmitted to the vapor, a fact which by itself must counteract evaporation, the metal of the heating elements owing to the lack of contact with the water will always be in danger of being seriously damaged.

A much better performance can be predicted for the case that the anti-foam agent accomplishes a hyrophilic conditioning of the heating surfaces as well as of the suspended particles. Then, any bubble formation inside the water must be extremely difficult even under sudden pressure reduction, and with the elimination of active centers on the heating surface creation of bubbles will be restricted to its immediate neighborhood. Since in the absence of catalyzing interfaces only a few bubbles can simultaneously originate each of them has the best opportunity of full size growing, while the perfect contact between the water and the heating surface provides for the most economical heat transfer. Under such circumstances the coalescence-preventing effects of electrolytes are evidently of minor concern.

Little seems to be known about what may afford proof in favor of these views. Research seems to have been largely on a trial and error basis. It is hoped, however, that a better theoretical understanding may soon contribute to progress of practical value.

Calendar of Meetings

December

1– 2 American Physical Society, Chicago, Illinois
12 Physics Club of Chicago, Chicago, Illinois
16 American Physical Society, Pasadena, California

January

9 Physics Club of Chicago, Chicago, Illinois
19–20 American Physical Society, New York, New York
22–26 American Institute of Electrical Engineers, New York, New York

February

13 Physics Club of Chicago, Chicago, Illinois
24 American Physical Society, Metropolitan Section, Columbia University, New York
28 American Society for Testing Materials, Pittsburgh, Pennsylvania

March

13 Physics Club of Chicago, Chicago, Illinois

April

10 Physics Club of Chicago, Chicago, Illinois
12–14 Optical Society of America, Cleveland, Ohio

May

8 Physics Club of Chicago, Chicago, Illinois

June

18–22 American Society for Testing Materials, Buffalo, New York
25–29 American Institute of Electrical Engineers, Detroit, Michigan

Here and There

Nobel Prize Awards

The 1943 Nobel Prize in Physics has been awarded to Dr. Otto Stern of the Carnegie Institute of Technology, Pittsburgh, Pennsylvania. Dr. Stern was born in Sohrau, Germany in 1888 and has held positions at the Technische Hochschule, Zurich and at the universities at Frankfurt, Rostock, and Hamburg. Since 1933 Dr. Stern has been research professor in the Research Laboratory of Molecular Physics at Carnegie Institute of Technology. In 1930 he was awarded an LL.D. by the University of California. The Nobel Prize award was made as a result of his research in molecular physics.

The 1944 Nobel Prize in Physics has been awarded to Dr. Isador Isaac Rabi of Columbia University. Dr. Rabi was born in 1898 and came from Austria to this country as a small boy. He received the degree of Bacheolor of Chemistry at Cornell in 1919 and his Ph.D. from Columbia in 1926 for work on the magnetic properties of crystals. In 1927 he received the Barnard Fellowship from Columbia and a fellowship from the International Education Board of the Rockefeller Foundation. He spent two years studying in Munich, Copenhagen, Hamburg, Leipzig, and Zurich. Since 1929 Dr. Rabi has been a professor at Columbia. In 1936 he received the semicentennial award in physical science by Sigma Xi at Cornell. His work has been primarily in the field of experimental work on the magnetic properties of atomic nuclei.

New Appointments

Dr. Mervin J. Kelly, Director of Research of Bell Telephone Laboratories, has been elected Executive Vice President of the Laboratories. Dr. Kelly has made substantial contributions to photoelectric cells for sound pictures; to the water-cooled tubes widely used for high power broadcasting; and to the vacuum tubes which make long distance telephony possible. He graduated from the University of Missouri in 1914 and received the Ph.D. from Chicago in 1918. In that year he entered the Laboratories as a research physicist. He became Vacuum-Tube Development Director in 1930 and Director of Research in 1936. Dr. Kelly has had charge of Bell Laboratories' development in radar and other important fields. He is an adviser to the government on technical war projects; a Fellow of the American Physical Society, American Institute of Electrical Engineers, Institute of Radio Engineers, Acoustical Society of America; and a member of the Directors of Industrial Research.

Alva B. Clark and Dr. Reginald L. Jones have been elected Vice Presidents of the Laboratories.

Mr. Clark was graduated from the University of Michigan in 1911 and then entered the American Telephone and Telegraph Company as a transmission engineer; in 1916 he was placed in charge of the group concerned with telephone repeaters. Gradually he assumed additional responsibilities, becoming toll transmission engineer in 1929. With his group he transferred to Bell Telephone Laboratories in 1934, and in 1940 he became Director of Systems Development. During the war he has been primarily responsible for the Laboratories' work on Signal Corps communication equipment. He recently made an extensive trip to the European battlefronts to observe that equipment in action. Mr. Clark is a Fellow of the American Institute of Electrical Engineers, Acoustical Society of America, and American Association for the Advancement of Science.

Dr. Jones graduated from Massachusetts Institute of Technology in 1909 and received the D.Sc. in 1911. In that year he took up research in Bell Telephone Laboratories and in 1914 was put in charge of the telephone transmission laboratory. During World War I he was a Captain in the Signal Corps. In 1923 he became head of the inspection engineering work of the Laboratories; in 1927, outside plant development engineer; and in 1928, Director of Apparatus Development. Dr. Jones is a Fellow of the American Physical Society, American Institute of Electrical Engineers, Acoustical Society of America, and American Association for the Advancement of Science.

Dr. Kelly and O. B. Blackwell were elected to the Board of Directors of the Laboratories. Formerly Vice President of the Laboratories, Mr. Blackwell on October 1 became Assistant Vice President of the American Telephone and Telegraph Company.

Creation of a new post, Director of Libraries, at the Massachusetts Institute of Technology, and appointment of Professor John E. Burchard, now Director of the Bemis Foundation, to this post was announced by Dr. Karl T. Compton, President of the Institute. Professor Burchard began his new duties on October 1, although he is continuing for the duration to give a large portion of his time to the important war work on which he has been engaged for the past four years. "As Director of Libraries," President Compton said, "Professor Burchard will assume administrative direction of the Institute library and museum system, but he will have as his immediate and major task the planning of a broadened program of library service. The plan envisages the Institute libraries becoming a great technical library service center for this part of the country and the development of a building and program which will contribute substantially to the cultural activities of the Institute community, especially in the field of the humanities."

Dr. Milton Harris has announced his resignation as Director of Research of the Textile Foundation and the Textile Research Institute, to become effective January 1, 1945. At that time, he and a number of members of the staff who have been working with him will continue their activities in a research and consulting organization to serve the textile and allied industries under the name of the Milton Harris Associates. Associated with him will be Dr. Lyman Fourt, who will be in charge of physics and biophysics; Henry A. Rutherford, in charge of organic development; and Arnold M. Sookne, in charge of physical-chemistry research. The laboratories will be located in Washington, D. C.

80th Birthday of William Gaertner

It was announced that Mr. William Gaertner of The Gaertner Scientific Corporation celebrated his 80th birthday on October 24, 1944. In a career of half a century he has made a distinct and lasting contribution to the field of modern science in the design and production of high grade precision instruments. Throughout the years, Mr. Gaertner has continued to serve as President and Treasurer of the Corporation and is still active in the development of new instruments and the improvement of old designs.

Electrochemical Society Awards

The Board of Directors of the Electrochemical Society, an international organization, has announced the award of the eighth Edward Goodrich Acheson Medal and Thousand Dollar Prize to Dr. William Blum, Chief of the Section of Electrochemistry, U. S. Bureau of Standards. Dr. Blum is to a very large measure responsible for the standardization of electroplating methods and of plating formulas. The formal presentation of the Gold Medal and $1000 Prize took place at the fall convention of the Electrochemical Society at Buffalo, New York, October 13, 1944.

New G. E. Electronics Plant

The General Electric Company has purchased a one hundred and fifty-five acre plot of ground in Liverpool, five miles from the city of Syracuse, New York, and, when necessary materials are released by the government, will build a new plant and make it the headquarters for its department of electronics. Definite plans for the proposed plant have not been made, but preliminary arrangements call for the erection of several buildings so landscaped that it has been suggested that the plant be called "Electronics Park."

Textile Foundation Research

The Board of Directors of the Textile Foundation of Washington, D. C. has decided upon the immediate transfer of its program of fundamental research in the field of textile science from the National Bureau of Standards, Washington, D. C., where this research program has been carried out for the last eight years, to a new location at Princeton, New Jersey, in a property provided by the Textile Research Institute, Inc., of New York. As a result of this transfer it becomes possible to integrate the research effort of the Textile Foundation with the program of training and education at the graduate level which forms one of the five objectives of the Textile Research Institute in its campaign to provide the whole textile industry, covering natural and synthetic fibers alike, with a research organization and personnel adequate to the needs and problems of the postwar era.

Through the courtesy of President H. W. Dodds of Princeton University the Textile Foundation has secured the part-time services of Professor Henry Eyring as Acting Director of the research program of the Textile Foundation and the Textile Research Institute. Under his direction it is planned to engage immediately in a broad program of research effort in the chemistry and physics of fibers and to initiate, under a fellowship plan, the educational activities of the Textile Research Institute. The decision to initiate this immediately instead of in the postwar period permits the research-training program to go into effect during the academic year 1944–45, thus advancing by at least a year the provision of trained personnel for the postwar era.

Dr. Robert E. Rose, of Penn's Grove, New Jersey, who recently retired from his position as director of the E. I. du Pont de Nemours & Company technical laboratory, and who is Chairman of the Scientific Advisory Committees of both the Textile Foundation and the Textile Research Institute, has agreed to associate himself with the development as Research Counselor of both organizations, and will cooperate with Professor Eyring in the solution of the problems involved.

General Motors Conferences

The application of spectrochemical analysis has expanded so rapidly in General Motors Corporation in connection with war production problems that there are now twenty-four General Motors plants which have spectrographic installations in operation or on order. In order to develop further the applications of these analytical tools the spectroscopists in the Corporation have initiated a series of General Motors Spectrographic Conferences. Since such conferences are attended only by General Motors men, they provide for frank and critical examination of spectrographic methods now in use or contemplated in the Corporation. The fundamental physical and chemical aspects of the field are also discussed, together with closely associated problems of physics, chemistry, and metallurgy. Five of these conferences have been held at intervals of about three months, and have been attended by from forty to sixty men. At these meetings, papers have been presented by R. E. Nusbaum and D. L. Fry of the Research Laboratories Division, S. F. Simpson of Chevrolet; W. N. Hatfield of Delco-Remy, R. W. Smith of AC Spark Plug, H. H. Grossman of Harrison Radiator, E. Osborne of Buick, F. D. Brookshire and W. R. O'Neill of Cadillac Motor, L. A. Danse of Standards Section, and R. B. Schenck of Buick. Further meetings are planned, together with other activities such as the cooperative preparation of standards and the extensive study of methods and equipment. Temporary Chairman of the group during its formative period is G. M. Rassweiler, Research Laboratories Division.

Bulletin of Mathematical Biophysics

The December, 1944 issue of the *Bulletin of Mathematical Biophysics*, Vol. 6, No. 4, will have the following table of contents:

On the Theory of Blood-Tissue Exchanges: I. Applications—R. E. SMITH AND M. F. MORALES.
On the Theory of Blood-Tissue Exchanges: II. Circulation and Inert-Gas Exchanges at the Lung with Special Reference to Saturation—M. F. MORALES AND R. E. SMITH.
On the Form and Strength of Trees: Part II. The Primary Branches—I. OPATOWSKI.
The Two-Factor Theory of Nervous Excitation with Non-Normal Accommodation—ALSTON S. HOUSEHOLDER.
Contributions to the Mathematical Biophysics of Visual Aesthetics—N. RASHEVSKY AND VIRGINIA BROWN.

Book of A.S.T.M. Standards

Heavy demands for the 1942 *Book of A.S.T.M. Standards* and its Supplements occasioned by the war production efforts have necessitated advancing by a full year publication of the next book. Normally this would come out in November-December, 1945 on the triennial basis, but the book will be issued in December, 1944.

Very widely used by American industry and many branches of state and federal governments, this book, providing authoritative specifications and tests for a wide range of engineering materials, will cover some 6000 pages in three parts: I, Metals; II, Non-metallic materials—constructional (cement, lime, concrete, paint, etc.); III, Non-metallic materials—general (petroleum, textiles, plastics, coal, rubber, etc.).

New Books

Electron-Optics

BY PAUL HATSCHEK, translated by Arthur Palme. Pp. 161+v, Figs. 125, 16×23½ cm. American Photographic Publishing Company, Boston, 1944. Price $3.00.

The book of P. Hatschek on electron optics, written in German nine years ago for "readers who had had no previous acquaintance with the subject," was translated and provided with an added chapter by Arthur Palme.

The reviewer has to start with an apology: Not knowing the original German edition he is at a loss to judge how many of the mistakes contained in the book are due to the author and how many to the translator. By deductive methods, so dear to the mystery writers, he thinks that he can ascribe the majority of them to the translator. The main reason for his assumption is an analysis of the notes and of the last chapter added by the translator. They show that the translator is imbued with a great deal of love and enthusiasm but with considerably less knowledge. Unfortunately for the translation of this type of book some

knowledge of the subject is necessary. By using the deductive methods of Sherlock Holmes one would be inclined to say that the translator is familiar with what is commonly known as electronics. This electronics of electrical engineering and allied branches is by no means equivalent to the physics of electrons, and even further away from optics. Only such a lack of knowledge of the physical principles can explain such unfortunate remarks, as the note by the translator on p. 91, when commenting on the resolving power of light microscopes: "Mention should be made here that somewhat higher magnification can be obtained with ultraviolet illumination. The image cannot be seen by the eye, but can be readily photographed. The fact that the multilens system of a microscope blocks a very large proportion of the ultraviolet light, glass being almost opaque to these rays, necessitates extremely long exposures."

The available space doesn't allow me to quote many mistakes or to investigate whether it's the translator's or the author's fault to have garbled some of the explanations like, for instance, that of the resolving power on pp. 89–90. But another feature of the book should be pointed out which is a direct consequence of the translator's unfamiliarity with the subject. Very often in the book developments in different fields are represented as having essentially been done in Germany. Inasmuch as such a procedure is understandable (but not excusable) in a German book written for the Germans, it is hard to understand why the translator didn't try to remedy the situation by means of some added notes. So, for instance, speaking of radio tubes, Lieben's name figures prominently without mentioning de Forest. Also where the translator refers to modern developments since the publication of the German book, his knowledge is limited to commercial publicity alone and there is no evidence for his having read very much of the scientific and technical publications on the subject.

In spite of all these limitations the book is not without merit. Many of its explanations are very well presented and might serve advantageously as an introduction to electron optics for the lay public. The translator is certainly right in his remark that "the fundamentals presented in this book will always have a permanent worth in the history of electronics."

The book is, with few exceptions, well illustrated and excellently printed on very good paper. The publishing house has to be complimented on the presentation of the book.

L. Marton
Division of Electron Optics
Stanford University

Electronic Physics

By L. G. Hector, H. S. Lein, and C. E. Scouten. Pp. 355+viii, Figs. 289, 15×22 cm. The Blakiston Company, Philadelphia. Price $3.75.

As an elementary approach to electricity and light, this attractive volume has much to recommend it. It seems to be based upon the hypothesis that students can be taught electricity from the modern viewpoint without a prolonged apprenticeship in mechanics, heat, and sound, and without going through the whole historical development of electricity. The emphasis is upon practical matters, and practical units only are employed throughout. The use of mathematics is strictly limited: arithmetic and algebra, and no trigonometry, not even in the parts on alternating current. The book should be about right for high school students or for first-year college students. In the latter case, it should serve for a one-semester course only, unless the students are inordinately slow.

The line drawings are done in two tones, black and red, a device which adds to the figures a degree of life not ordinarily encountered. In many cases, this method of using two colors allows the artist (Anne Scouten) to bring out essential details clearly in simple drawings. The text breaks into the modern verbiage of electronics quickly and treats electricity almost from the start from the electron viewpoint, but it retains the conventional directions of current, lines of force, etc. The style is simple and readable and not involved.

Each chapter is introduced by a paragraph stating the aims to be attained, and concluded with a series of numbered items summarizing the principal points encountered. There are two groups of graded problems at the end of each chapter; the more difficult group should not strain the mentality of an alert college freshman. Suggestions for simple experiments are also included, although the book is in no sense a laboratory manual. Two or three color plates help to dress it up.

Approximately 60 percent of the book is devoted to electricity, proceeding farther on alternating current than most high school texts do, but not going into radio and other electronic applications as far as the title of the book would suggest. Only two chapters are devoted to wireless and radio as such. There follows 30 percent of the book on light, and the rest is devoted to two final chapters on radioactivity and modern nuclear physics. In view of the contents cited, the book might be used as the text for a half-year of general physics at the introductory level. The authors have tried successfully to break away from some of the traditional methods of approach in electricity (not so much in light) but their finished product is by no means revolutionary either in content or approach.

Richard M. Sutton
Haverford College

New Booklets

Catalog EN-95 is the new revised booklet, *Apparatus for Electrolytic Conductivity Measurements in Laboratory and Plant*, which describes instruments for making precise conductivity measurements in plant, laboratory, or classroom. This publication presents much the same data about methods of measurement and notes for selection and use of the apparatus as did the previous edition. But, in addition,

it illustrates and describes a signalling conductivity controller and several new industrial cells which have become available since the earlier edition was issued. For a copy of this 44-page catalog, EN-95, 1944 edition, write to Leeds and Northrup Company, 4934 Stenton Avenue, Philadelphia 44, Pennsylvania.

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Letters to the Editor

Representation of Rigid Rotations

I. F. Morrison
University of Alberta, Edmonton, Alberta, Canada
September 6, 1944

In the August issue of the *Journal of Applied Physics*, E. T. Benedikt* works out an interesting form of an operator which, when applied to a vector r, causes a finite rotation of amplitude θ around a unit vector h.

The process by which the final result is obtained is, perhaps, longer than necessary and there are one or two points of added interest which may be worth pointing out.

The equation

$$r'=r+(\cos\theta-1)[r-h^2r]+\sin h\times r \qquad (2)$$

would be in better form if, when factored, it were written

$$r'=\{I+(\cos\theta-1)(I-hh)+\sin\theta(I\times h)\}\cdot r,$$

in which I is the idemfactor. This makes the terms homogeneous in character and the operator

$$\mathfrak{R}\equiv I+(\cos\theta-1)(I-hh)+\sin\theta(I\times h)$$

then becomes a proper dyadic, or tensor if one prefers.

Now it is well known that, in vector algebra, the dyadic $I\times h$ behaves like the scalar $\sqrt{-1}$ in ordinary algebra. Suppose, therefore, we examine the expansion of $e^{\theta(I\times h)}$. This is:

$$e^{\theta(I\times h)}=I+\theta(I\times h)+(\theta^2/2!)(I\times h)^2+(\theta^3/3!)(I\times h)^3+\cdots$$

It is easy to show that

$$(I\times h)^2=-(I-hh),\ (I\times h)^3=-(I\times h),\ (I\times h)^4=+(I-hh),\ \text{etc.}$$

Substituting, we have

$$hh+(I-hh)+\theta(I\times h)-(\theta^2/2!)(I-hh)-(\theta^3/3!)(I\times h)+(\theta^4/4!)(I-hh)+(\theta^5/5!)(I\times h)-\cdots,$$

and obviously this can be rearranged into

$$hh+(I-hh)[1-(\theta^2/2!)+(\theta^4/4!)-\cdots]+(I\times h)[\theta-(\theta^3/3!)+(\theta^5/5!)-\cdots]=hh+(I-hh)\cos\theta+(I\times h)\sin\theta,$$

or

$$I+(\cos\theta-1)(I-hh)+\sin\theta(I\times h)\equiv\mathfrak{R},$$

which is equivalent to the operator sought.

* See E. T. Benedikt, J. App. Phys. 15, 613 (1944).

Representation of Rigid Rotations

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September 4, 1944

The very interesting article by Mr. Elliot T. Benedikt on the representation of rigid rotations* gives a remarkably simple expression of rigid rotations, which should eliminate the use of Hamilton's quaternions. The following demonstration of the relation

$$\mathbf{r}'=(\exp\boldsymbol{\theta}\times)\mathbf{r}$$

appears to be somewhat simpler than that of the author, and has the advantage of showing the geometrical origin of the formula. Considering the rotation $\boldsymbol{\theta}$ as an infinite sum of infinitely small rotations

$$\boldsymbol{\theta}/m=(\theta/m)\mathbf{h}$$

for each infinitely small rotation [which corresponds to a displacement perpendicular to both vectors $\boldsymbol{\theta}$ and $\mathbf{r}(n\theta/m)$, the latter being obtained after n rotations $\boldsymbol{\theta}/m$], it can be written

$$\mathbf{r}'[(n+1)\theta/m]=\mathbf{r}'(n\theta/m)+(\boldsymbol{\theta}/m)\times\mathbf{r}'(n\theta/m)=[1+(\boldsymbol{\theta}/m)\times]\mathbf{r}'(n\theta/m)=[1+(\boldsymbol{\theta}/m)\times]^{n+1}\mathbf{r}.$$

Thus

$$\mathbf{r}'=\lim_{m=\infty}[1+(\boldsymbol{\theta}/m)\times]^m\mathbf{r}.$$

Developing the infinite product, it can be shown, exactly in the same manner as in conventional calculus, that the infinite product is equal to an infinite sum, which is the definition of the exponential. This proves the relation

$$\mathbf{r}'=(\exp\boldsymbol{\theta}\times)\mathbf{r}.$$

* See E. T. Benedikt, J. App. Phys. 15, 613 (1944).

Contributed Original Research

On the Silica Replica Method of Surface Examination with the Electron Microscope

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(Received August 17, 1944)

An essential step in the making of a silica replica by the Heidenreich technique consists in the evaporation of silica in a high vacuum. An alternate method for depositing silica has been investigated and is discussed in this paper. This method consists in the chemical deposition of silica from the compound $SiCl_4$.

IN the last few years a number of techniques for making replicas for the electron microscope observation of surfaces have been described.[1–4]

One of these methods, originated by Heidenreich and Peck, has met with considerable success, and is finding increasing application particularly in the field of metallurgy. Obtaining replicas by this technique is a two-stage process. Polystyrene is first molded, at high temperature and pressure, to the surface of the specimen. After the excess polystyrene has been trimmed away, the remainder of the block is separated from the specimen either by dissolving the specimen or by mechanically splitting off the polystyrene block. This provides a negative impression of the surface in the polystyrene. Silica is then evaporated in a high vacuum chamber onto the polystyrene surface, forming a thin film, which when removed in a suitable solvent and mounted on a fine metal screen is ready for observation in the electron microscope.

The evaporation of silica when properly carried out is not at all difficult. However, it does require —in addition to expensive vacuum and electrical equipment of a type not found in many laboratories—a familiarity with high vacuum techniques. In view of this the authors realized that the silica replica technique would be made available to a larger group if the evaporation step could be simplified or eradicated. In addition, homogeneous silica films would be more widely used as specimen supports if their production were to be simplified. The fact that silica films are mechanically strong, thermally stable, and sufficiently structureless, and hence make excel-

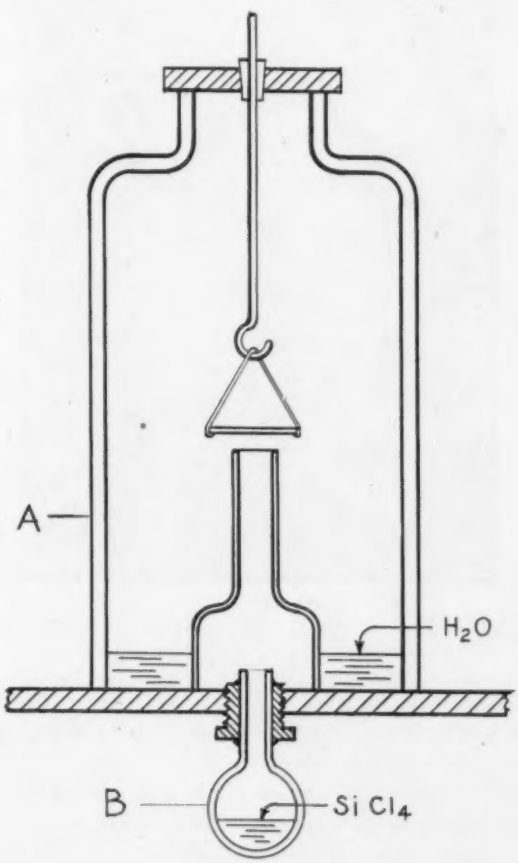

FIG. 1.

[1] H. Mahl, Zeits. f. tech. Physik **21**, 17 (1940).
[2] V. K. Zworykin and E. G. Ramberg, J. App. Phys. **12**, 642 (1941).
[3] V. J. Schaefer and D. Harker, J. App. Phys. **13**, 427 (1942).
[4] R. D. Heidenreich and V. G. Peck, J. App. Phys. **14**, 23 (1943).

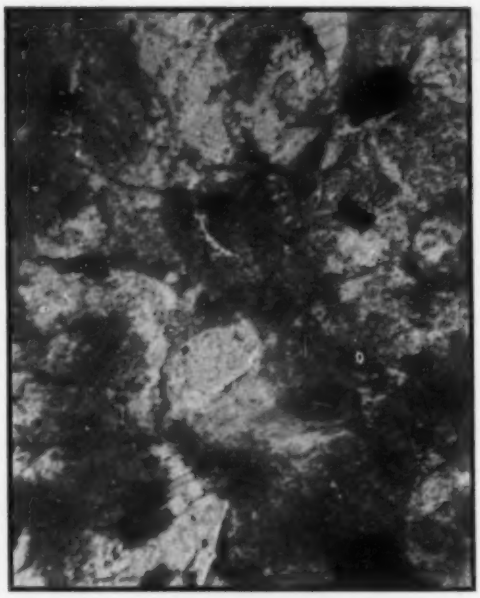

FIG. 2(a). Frosted light bulb surface. Positive replica produced by chemical deposition of silica. 31,500×.

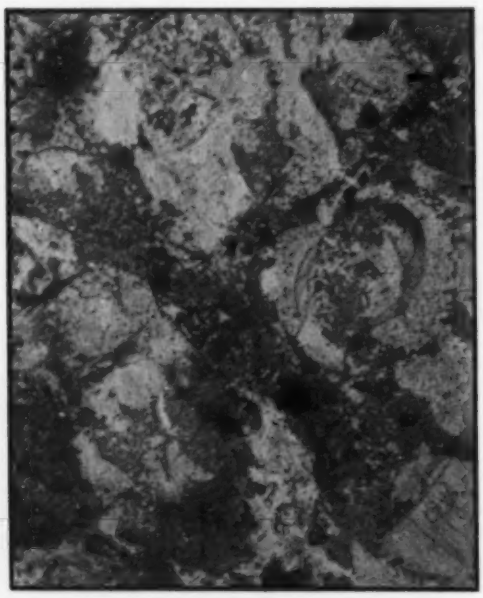

FIG. 2(b). Frosted light bulb surface. Positive replica produced by evaporation of silica. 31,500×.

lent specimen supporting films, has been pointed out by Heidenreich and Peck.[4]

The purpose of this note is to describe some preliminary experiments which were made to determine whether or not silica could be deposited chemically in a way which would be satisfactory both for the production of homogeneous support films and for the preparation of surface replicas. An attractive possibility appeared to be the production of SiO_2 by way of a chemical reaction involving a silicon compound, the SiO_2 being deposited on the polystyrene replica either from the vapor or the liquid phase. Two factors are of prime importance and must be controllable if the method is to be successful. These are the rate and uniformity of deposition of the resulting silica film.

A hydrolysis reaction was chosen for these experiments because of its convenience. Of the several silicon compounds which lend themselves to a hydrolysis reaction, silicon tetrachloride was used chiefly because it happened to be cheap and readily available. The hydrolysis of silicon tetrachloride proceeds according to the reaction:

$$SiCl_4+2HOH\rightarrow SiO_2+4HCl.$$

Silicon tetrachloride is a liquid at room temperature, boiling at 59.6°C.

The experimental problem of obtaining a silica film by this method is that of introducing the two components at suitable vapor pressure on to the polystyrene surface. The vapor pressures at the surface and any adsorbed water vapor on the surface obviously determine the time necessary to deposit a film of optimum thickness. Several techniques were tried and will be described.

The first method tried was to dip the polystyrene surface in $SiCl_4$ solution and then whirl it rapidly on a turntable in moist air. While this method might be useful in forming structureless films on a smooth polished polystyrene surface, it has obvious disadvantages for making replicas because of the roughness of the surface. No useful replicas were made by this method.

Some attention was paid to the possibility of diluting the $SiCl_4$ with a wet organic compound and thus carrying out the reaction entirely in the liquid phase, but the speed of the reaction made this method impractical.

In this connection it may be noted that some efforts were made to spread structureless silica films on a water surface in much the same manner as collodion films are spread using an amyl acetate solution. The water was diluted with ethylene glycol and a drop of $SiCl_4$-amyl acetate solution was applied to the surface of the water solution with a medicine dropper. It was not found possible to attain a sufficiently low concentration of water. In fact, the prevailing

atmospheric humidity was found to be a limiting factor emphasizing the need for strict air conditioning. Several methods of introducing the vapors directly on the polystyrene were tried. Two of these depended on atmospheric humidity to furnish water vapor. In the first a jet of $SiCl_4$ was directed at the surface. The speed of the reaction was attested to by the immediate formation of a white cloud of SiO_2 between the jet and the surface. In the second the polystyrene was supported a few centimeters above a dish containing $SiCl_4$. Care was taken to eliminate or minimize thermal currents of air which would introduce irregularities. In both these methods the rate of film formation depended on the relative humidity prevailing at the time.

The final method used allowed more control. The apparatus used is shown in the schematic diagram Fig. 1. *A* is a bottle approximately 5 inches in diameter and 10 inches high which contained a small volume of water and ethylene glycol. Through a hole in the bottom of this bottle a tube was sealed leading to a small bottle *B*, containing $SiCl_4$. This bottle was removable by means of a threaded joint and the opening could be closed with a rubber stopper. The surface to be coated was supported at the end of a wire which had a rubber stopper at the other end. The length of the wire was such that the polystyrene was approximately $\frac{1}{4}''$ from the upper end of the glass tube leading to the $SiCl_4$ bottle. The procedure used in depositing a film was to insert the specimen, which had been slightly warmed, in the bottle *A* and let it come to equilibrium with the water vapor for a few minutes. Then the stopper in the bottom was taken out and the $SiCl_4$ bottle quickly screwed into place. The rate of the reaction is controlled by the percentage of ethylene glycol in the water.

As a time calibration of the method, it was found convenient to insert a piece of lead glass into the chamber. The time necessary to form a light brown interference color on the glass served to give a measure of the rate of reaction, and the deposition time for a film of any given thickness could then be calculated.

As a test of the method a number of structureless silica films were successfully deposited on fire-polished polystyrene. This showed first, that the method under proper conditions introduced no structure peculiar to itself and second, that the production of silica films to be used as specimen supports was feasible. As a further test a polystyrene replica was made of the inside surface of an ordinary frosted light bulb. The polystyrene was cut and quartz evaporated onto one-half in the usual way. The other half was treated as described. Electron micrographs of the resulting two silica replicas are shown in Fig. 2.

FIG. 3. Non-reflecting film on window glass. 31,500×. Positive replica produced by chemical deposition of silica.

Figure 3 is a replica of a portion of a non-reflecting film on window glass. The long parallel lines are apparently peculiar to the process of manufacture of the glass. The characteristic skeletonized structure of non-reflecting silica films[5] is seen superimposed on the parallel lines.

Two types of failure were encountered (using the last method). The film did not always come off in the solvent in one piece but appeared to be colloidal in nature. Secondly, the film sometimes exhibited a grainy structure. It is to be emphasized that the method described above did not give consistently reproducible results. In spite of this it was felt that publication was justified at this stage, primarily to call the general method to the attention of interested workers who may be able to bring to bear on the problem sufficient time and experience to refine the technique and make it generally useful and dependable.

The authors wish to thank Dr. James Hillier for many helpful suggestions.

[5] F. H. Nicoll and F. E. Williams, J. Opt. Soc. Am. **33**, 434 (1943).

X-Ray Measurement of Order in the Alloy Cu_3Au*

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(Received July 18, 1944)

X-ray diffraction theory is developed for the evaluation of long range order and short range order in the alloy Cu_3Au, and experiments are described whereby each type of order was measured. Values of the long range order parameter S were found to be 0.86 for 250°C, 0.81 for 370°C, and 0.79 for 380°C, the samples being held at elevated temperatures during the x-ray exposures. At the critical temperature $T_c=388$°C, S suddenly dropped to zero. Above T_c short range order was found to exist, the amount present being specified by a set of parameters σ_i which are associated with the interatomic distances r_i. The dominant short range order parameter σ_1, referring to nearest neighbors, was evaluated as 0.50 for 540°C and 0.25 for 750°C.

DIFFRACTION THEORY FOR LONG RANGE ORDER

IN the study of long range order in Cu_3Au by the x-ray powder method one encounters two sets of lines (see Fig. 1). One set, which is

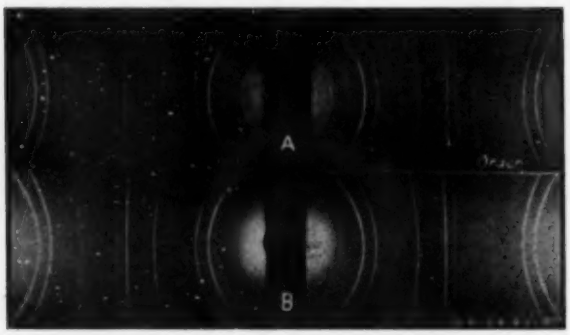

FIG. 1. Powder patterns for (A) ordered Cu_3Au and (B) disordered Cu_3Au.

independent of order, will be referred to as the fundamental lines. The other set, the superstructure lines, appears only when long range order is present, the intensity of any line in this set being a simple function of order. Hence, by comparing the intensity of a superstructure line with that of a fundamental line, one can evaluate the degree of long range order present.

A theoretical approach to the problem can be conveniently made by considering a face-centered cubic lattice. Let the face centers be designated as α-sites and the cube corners as β-sites. If in an alloy of composition A_3B, all the A atoms are placed upon the α-sites and all the B atoms upon the β-sites, perfect order will result. For partial order only a fraction r_α of the A atoms are on the α-sites and a fraction r_β of the B atoms are on the β-sites. In terms of r_α and r_β Bragg and Williams[1] defined the long range order parameter S in such a manner that $S=1$ for perfect order, $S=0$ for utter lack of long range order, and S has intermediate values for degrees of order between these extremes. Applying this definition for long range order to the alloy A_3B, one obtains

$$S=4r_\alpha-3=\tfrac{1}{3}(4r_\beta-1). \tag{1}$$

For the alloy A_3B with any degree of order, the structure factor F is

$$F=\{f_Br_\beta+f_A(1-r_\beta)\}+\{f_Ar_\alpha+f_B(1-r_\alpha)\}\{\exp(i\pi\{h+k\})+\exp(i\pi\{k+l\})+\exp(i\pi\{l+h\})\}, \tag{2}$$

where f_A, f_B are the atomic scattering factors and h, k, l are the Miller indices. The structure factor for a fundamental line arising from a combination of all odd or all even Miller indices is

$$F_{\text{fund}}=3f_A+f_B. \tag{3}$$

For a superstructure line the indices h, k, l, are mixed odd and even, and the structure factor is

$$F_{ss}=(f_B-f_A)(r_\alpha+r_\beta-1). \tag{4}$$

With the help of Eq. (1), we can rewrite Eq. (4) in terms of S,

$$F_{ss}=(f_B-f_A)S. \tag{5}$$

* Extract from a thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics at the Massachusetts Institute of Technology.

† Now at the Radiation Laboratory, Massachusetts Institute of Technology.

[1] W. L. Bragg and E. J. Williams, Proc. Roy. Soc. **A145**, 699 (1934).

To obtain a practical explicit expression for S, it is necessary to state the general experimental conditions under which one wishes to make the observations. In the experiments described in this paper, a flat opaque sample of Cu_3Au powder was placed centrally in a Debye-Scherrer camera, the x-ray beam making a grazing angle ϕ with the plane of the sample. For a superstructure line, the power per unit length of line (integrated intensity) is then given by*

$$P_{ss}=\left\{\frac{I_0e^4\lambda^3N^2M(f_{Au}-f_{Cu})^2S^2(1+\cos^2 2\theta)}{256\pi m^2c^4R\sin\theta\sin 2\theta}\right\}\times\{\exp(-\overline{u^2}k^2)\}\left\{\frac{a}{\mu}\frac{\sin\phi\sin(2\theta-\phi)}{\sin\phi+\sin(2\theta-\phi)}\right\}, \quad (6)$$

where

N = number of atoms per unit volume of crystal,
M = multiplicity for a powder pattern,
$\exp(-\overline{u^2}k^2)$ = correction for temperature vibration of the atoms,[2,3]
$\overline{u^2}$ = mean square of the component of atomic displacement normal to the reflecting plane,
$k=4\pi(\sin\theta/\lambda)$,
a = area of the sample illuminated by the x-ray beam,
μ = linear absorption coefficient.

The first bracket in Eq. (6) is the value of the integrated intensity for a unit volume of crystalline material if one neglected temperature effects and absorption of radiation in the sample. The third bracket accounts for the absorption of the incident x-rays as they penetrate the sample and for the absorption of the emerging rays diffracted from the interior of the sample. (See appendix for details.) For a fundamental line, the integrated intensity is

$$P_{\text{fund}}=\left\{\frac{I_0e^4\lambda^3N^2M(f_{Au}+3f_{Cu})^2(1+\cos^2 2\theta)}{256\pi m^2c^4R\sin\theta\sin 2\theta}\right\}\times\{\exp(-\overline{u^2}k^2)\}\left\{\frac{a}{\mu}\frac{\sin\phi\sin(2\theta-\phi)}{\sin\phi+\sin(2\theta-\phi)}\right\}. \quad (7)$$

Dividing Eq. (6) by Eq. (7) one eliminates most of the troublesome constants, and obtains an expression that can be evaluated experimentally according to the following procedure. From a microphotometer trace of the diffraction photograph, an intensity curve in arbitrary units is constructed. On this curve, a powder pattern line appears as a region of high intensity, the area A under this intensity peak being proportional to the integrated intensity P. Hence

$$\frac{P_{ss}}{P_{\text{fund}}}=\frac{A_{ss}}{A_{\text{fund}}}, \quad (8)$$

and

$$S^2=\frac{\left\{\frac{M(f_{Au}+3f_{Cu})^2(1+\cos^2 2\theta)\sin(2\theta-\phi)}{A\sin\theta\sin 2\theta(\sin\phi+\sin\{2\theta-\phi\})}\exp(-\overline{u^2}k^2)\right\}_{\text{fund}}}{\left\{\frac{M(f_{Au}-f_{Cu})^2(1+\cos^2 2\theta)\sin(2\theta-\phi)}{A\sin\theta\sin 2\theta(\sin\phi+\sin\{2\theta-\phi\})}\exp(-\overline{u^2}k^2)\right\}_{ss}}. \quad (9)$$

The value of $\overline{u^2}$ can be obtained in an analogous manner from the integrated intensities of two fundamental lines.

EXPERIMENTAL RESULTS FOR LONG RANGE ORDER

A Debye-Scherrer type vacuum camera of radius $R=4.45$ cm was fitted with a small electric furnace so that the samples could be maintained at elevated temperatures during exposures. X-radiation consisting of the Cu $K\alpha$ lines monochromated by reflection from a rock-salt crystal, impinged upon the sample at a glancing angle of about 15°, the angle being measured to within 0.1° in each case. For evaluating S, the superstructure line 210 and the fundamental line 200 were chosen, while $\overline{u^2}$ was evaluated from the fundamental lines 200 and 220. In order to measure the 200 line conveniently, it was found helpful to attenuate this line

* The integrated intensities of the superstructure lines are independent of any antiphase domains which may be present. A proof of this, which has been developed by B. E. Warren, will be published later.

[2] I. Waller and R. W. James, Proc. Roy. Soc. **A117**, 214 (1927).

[3] W. H. Zachariasen, Phys. Rev. **57**, 597 (1940).

to 0.502 of its original intensity by means of an aluminum mask. The final experimental results are listed in Table I. In Fig. 2 these experimental

TABLE I. Experimental results for long range order.

Temperature °C	$\frac{A_{s}}{A_{\text{fund}}}$	ϕ	$\overline{u^2}$	S
250	0.249	15.0	0.038	0.86
370	0.205	14.5	0.062	0.81
380	0.202	14.5	0.053	0.79

results are compared with the theoretical prediction of Peierls[4, 5] and Bragg and Williams.[1, 5]

As a supplement to the main experiments, the critical temperature T_c was determined photographically. From electron diffraction experiments, Germer, Haworth, and Lander[6] observed that the superstructure lines began to be gradually less prominent at 300°C and finally disappeared at 370°C. By other methods, various experimenters found T_c to lie between 385°C and 394°C and to appear at a well-defined discontinuity between the ordered and disordered states. The x-ray diffraction photographs used in determining T_c are shown in Fig. 3. One observes that at 386.0°C, the superstructure lines are prominent, at 387.5°C these lines are very faint, and at 389.0°C they have disappeared completely. From these observations, the probable value of T_c is estimated to be 388°C. It can be conservatively stated that the temperatures are correct to within 5°C although the precision with which the temperature could be read was 0.1°C, and the temperature fluctuation during exposures was less than ±0.2°C. From the foregoing observations it is reasonable to conclude that the x-ray diffraction method of investigating the transition from order to disorder is in general agreement with most of the other methods with regard to the value of T_c, and that this transition is found to be quite abrupt.

DIFFRACTION THEORY FOR SHORT RANGE ORDER

The following development is based on the assumption that long range order is not present. It will be shown that for a powder pattern, the diffracted x-radiation consists of a set of crystalline reflections, the fundamental lines, superimposed on a diffuse background, the amount of short range order being evaluated from this background. For a convenient starting point, one can choose the equation

$$I=\sum_{l}\sum_{l'} f_l f_{l'} \frac{\sin kr_{ll'}}{kr_{ll'}}, \qquad (10)$$

where I is the intensity of diffracted radiation in electron units, k is $(4\pi \sin\theta)/\lambda$, and $r_{ll'}$ is the distance between the lth and the l'th atoms. Equation (10) can be put into a more usable form by re-arranging the terms according to the

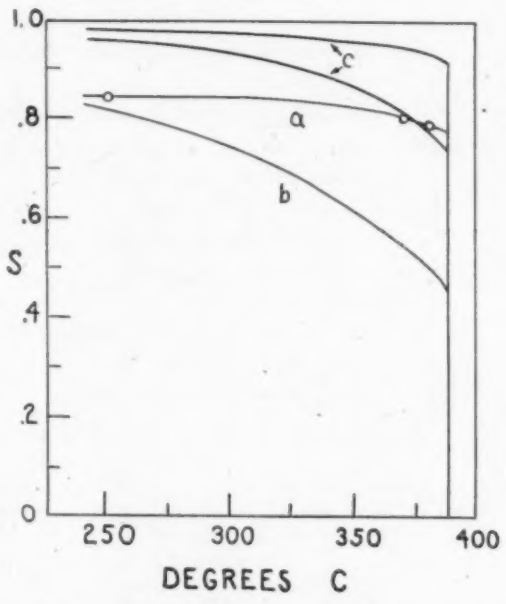

FIG. 2. Long range order parameter S as a function of temperature: (*a*) experimental, (*b*) Bragg and Williams' theory, (*c*) Peierls' theory.

values of $r_{ll'}$. Let the distance between nearest neighbors be designated r_1, between second neighbor r_2, etc. An atom of type B in the alloy A_3B will have on the average, say n_i neighbors of type A at distance r_i, the total number of ith neighbors being designated by c_i. For interatomic distances $r_i > r_m$, where m is sufficiently large, it will be assumed that a condition of randomness exists. Finally, let N_0 be the total number of diffracting atoms. In terms of the above notation and with the help of elementary statistical consideration, one can express the probability that $f_l f_{l'}$ is $f_A f_A$, $f_B f_B$, or

[4] R. Peierls, Proc. Roy. Soc. **A154**, 207 (1936).
[5] F. C. Nix and W. Shockley, Rev. Mod. Phys. **10**, 1 (1938).
[6] L. H. Germer, F. E. Haworth, and J. J. Lander, Phys. Rev. **61**, 93 (1942).

$f_A f_B$. Incorporating these concepts into Eq. (10) one obtains,

$$I=\sum_{l=l'}\sum_{l'} f_l f_{l'}+\sum_{l}^{m}\sum_{i=1}^{l'} f_l f_{l'}\frac{\sin kr_i}{kr_i}$$

$$+\sum_{l}\sum_{i>m}^{l'} f_l f_{l'}\frac{\sin kr_i}{kr_i}$$

$$=\{N_0(\tfrac{3}{4}f_A{}^2+\tfrac{1}{4}f_B{}^2)-N_0(\tfrac{3}{4}f_A+\tfrac{1}{4}f_B)^2\}$$

$$+\left\{\sum_{i=1}^{m}\sum\left\{\frac{1}{4}f_B\left(\frac{n_i}{c_i}f_A+\frac{c_i-n_i}{c_i}f_B\right)\right.\right.$$

$$\left.+\frac{3}{4}f_A\left(\frac{n_i}{3c_i}f_B+\frac{3c_i-n_i}{3c_i}f_A\right)\right\}\frac{\sin kr_i}{kr_i}$$

$$\left.-\sum_{i=1}^{m}\sum(\tfrac{3}{4}f_A+\tfrac{1}{4}f_B)^2\frac{\sin kr_i}{kr_i}\right\}$$

$$+\left\{N_0(\tfrac{3}{4}f_A+\tfrac{1}{4}f_B)^2+\sum_{i=1}^{m}\sum(\tfrac{3}{4}f_A+\tfrac{1}{4}f_B)^2\right.$$

$$\left.\times\frac{\sin kr_i}{kr_i}+\sum_{i>m}\sum(\tfrac{3}{4}f_A+\tfrac{1}{4}f_B)^2\frac{\sin kr_i}{kr_i}\right\}$$

$$=\frac{3}{16}N_0(f_A-f_B)^2+\frac{N_0}{16}(f_A-f_B)^2$$

$$\times\sum_{i=1}^{m}c_i\left(3-\frac{4n_i}{c_i}\right)\frac{\sin kr_i}{kr_i}$$

$$+(\tfrac{3}{4}f_A+\tfrac{1}{4}f_B)^2\sum_{l}\sum_{l'}\frac{\sin kr_{ll'}}{kr_{ll'}},\quad(11)$$

or abbreviating,

$$I=N_0I_R+N_0I_{SRO}+CR\quad(12)$$

where

$$I_R=\tfrac{3}{16}(f_A-f_B)^2,$$

$$I_{SRO}=(f_A-f_B)^2\sum_{i}\frac{c_i}{16}\left(3-\frac{4n_i}{c_i}\right)\frac{\sin kr_i}{kr_i},$$

and

$$CR=(\tfrac{3}{4}f_A+\tfrac{1}{4}f_B)^2\sum_{l}\sum_{l'}\frac{\sin kr_{ll'}}{kr_{ll'}}.$$

The term I_R is a diffuse scattering owing to a condition of randomness, that is, lack of long range order; I_{SRO} is a fluctuating diffuse scattering owing to the presence of short range order; and CR represents a set of crystalline reflections, namely, the fundamental lines.

A complete expression for the total background intensity I_B must include a Compton modified scattering term I_C and a temperature diffuse scattering term I_T. Hence

$$I_B=I_R+I_{SRO}+I_C+I_T,\quad(13)$$

all quantities being in electron units per atom. The expression used for I_T is[3]

$$I_T=(\tfrac{3}{4}f_A+\tfrac{1}{4}f_B)^2\{1-\exp(-\overline{u^2}k^2)\}.$$

This expression for I_T follows from the old theory of the temperature diffuse scattering. It is taken as a good enough approximation for this work since we are not interested in the form of the diffuse scattering in the vicinity of a diffraction maximum.

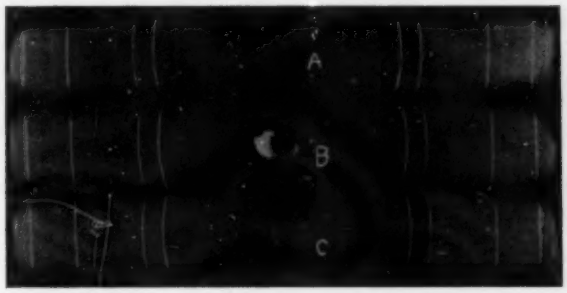

FIG. 3. Diffraction photographs for determining the critical temperature. Samples were held at elevated temperatures (A) 386°C, (B) 387.5°C, (C) 389.0°C.

The degree of short range order may be defined by a set of parameters σ_i such that $\sigma_i=0$ for total disorder and $\sigma_i=1$ for perfect order. Considering the crystal structures of Cu_3Au in terms of four interpenetrating simple cubic lattices we can write

$$\sigma_i=\frac{4n_i}{c_i}-3\quad(14a)$$

when the ith neighbors are not on the same simple cubic lattice as the reference atom, and

$$\sigma_i=1-\frac{4}{3}\frac{n_i}{c_i}\quad(14b)$$

when the ith neighbors are on the same simple cubic lattice as the reference atom. Thus

$$\sigma_1=4\frac{n_1}{c_1}-3,\quad\sigma_2=1-\frac{4}{3}\frac{n_2}{c_2},\quad\sigma_3=4\frac{n_3}{c_3}-3,\text{ etc.}$$

FIG. 4. Powder patterns used in the study of short range order. Photograph (A) is for sample quenched from 540°C, (B) for sample quenched from 750°C, and (C) for ordered sample. The 200 line in each case was attenuated to 0.251 of its original intensity by an aluminum mask. The fluctuating diffuse background in (A) indicates presence of short range order.

It can be easily verified that σ_1 is the short range order parameter σ as defined by Bethe.[7] For convenience in continuing the analysis let

$$\frac{c_i}{16}\left(3-\frac{4n_i}{c_i}\right)=\rho_i,$$

then

$$I_{SRO}=(f_A-f_B)^2\sum_i \rho_i\frac{\sin kr_i}{kr_i}. \qquad (15)$$

Replacing the summation by an integral, one obtains

$$I_{SRO}=(f_A-f_B)^2\int_0^\infty 4\pi r^2\rho(r)\frac{\sin kr}{kr}dr \qquad (16)$$

and

$$4\pi\int_0^\infty r\rho(r)\sin kr = \frac{k}{(f_A-f_B)^2}(I_B-I_R-I_C-I_T). \qquad (17)$$

Equation (17) can be solved for $\rho(r)$ by the methods of Fourier integral analysis.[8,9] Finally

$$\sigma_i=-\frac{16}{c_i}\int 4\pi r^2\rho(r)dr \qquad (18a)$$

corresponding to Eq. (14a) and

$$\sigma_i=\frac{16}{3c_i}\int 4\pi r^2\rho(r)dr \qquad (18b)$$

corresponding to Eq. (14b), the integrals being evaluated in the neighborhood of r_i.

EXPERIMENTAL RESULTS FOR SHORT RANGE ORDER

The samples used for the determination of short range order were quenched from elevated temperatures and diffraction patterns were obtained from the cold samples. In order to eliminate the possibility of fluorescence Au radiation fogging the photographic film, the radiation from a copper target was reflected from a fluorite crystal* so that only the strong Cu $K\alpha$ lines entered the camera. In other respects, the set-up was the same as that used for the determination of long range order.

An endeavor was made to arrange the experimental conditions to facilitate the observation

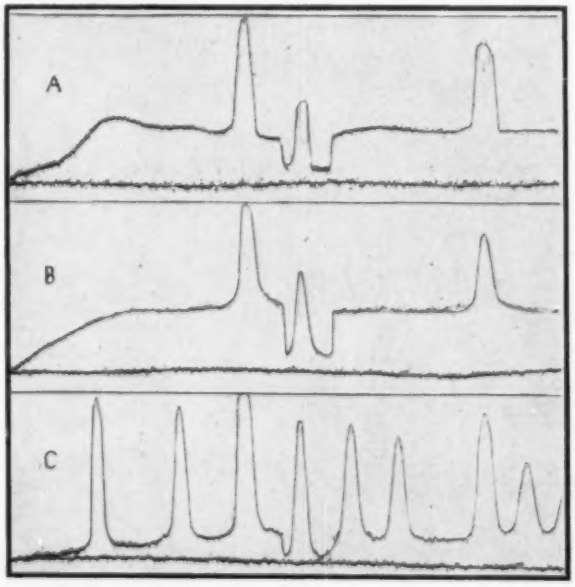

FIG. 5. Microphotometer traces of photographs shown in Fig. 4. Trace (A) is for 540°C, (B) 750°C, (C) ordered sample.

[7] H. A. Bethe, Proc. Roy. Soc. **A150**, 552 (1935).
[8] F. Zernicke and J. A. Prins, Zeits. f. Physik **41**, 184 (1927).
[9] G. C. Danielson and C. Lanczos, J. Frank. Inst. **233**, 365, 435 (1942).

* If rocksalt were used to reflect the Cu $K\alpha$ lines ($\lambda=1.54$A) from the 200 planes, then $\lambda=0.77$A from the continuous spectrum would also enter the camera. Since the L_I critical absorption wave-length for gold is 0.86A, fluorescence gold L_I radiation would be produced under these conditions. The 111 planes of fluorite, on the other hand, will reflect $\lambda=1.54$A strongly, and $\lambda=0.77$A very feebly, thus greatly minimizing the excitation of the fluorescence gold L_I radiation.

of short range order effects. An examination of the summation in Eq. (15) shows that the leading and dominant term has a maximum near $\theta=12°$. In order to include this significant region on the diffraction patterns, each sample was placed so that the x-ray beam made a grazing angle ϕ of about 12° with the plane of the sample. To insure backgrounds of sufficient density on the diffraction photographs, the samples were about two millimeters wide and the exposure times were in the neighborhood of 100 hours.

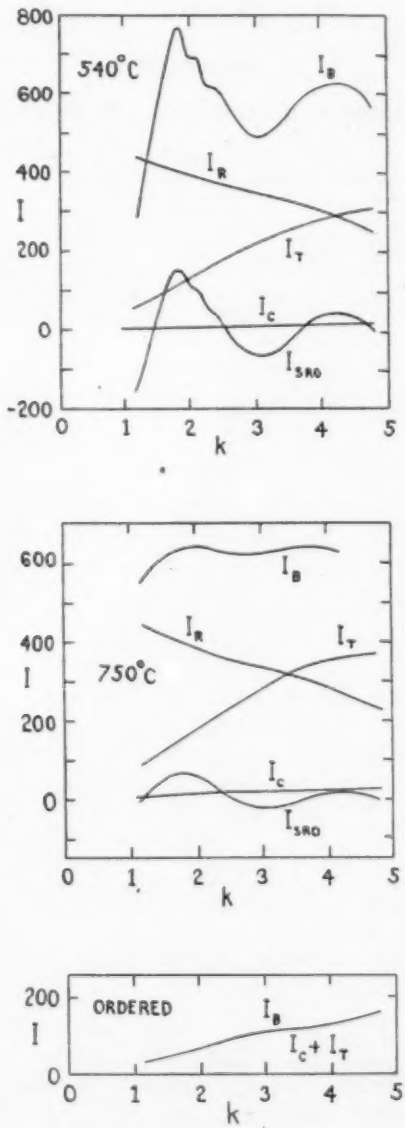

FIG. 6. Background intensities I_B are broken down into their components I_C, I_T, I_R, and I_{SRO}. Ordinate scale I is in electron units per atom, and abscissa is in units of $k=4(\pi/\lambda)\sin\theta$. For the ordered sample, it was found that $I_B=I_C+I_T$.

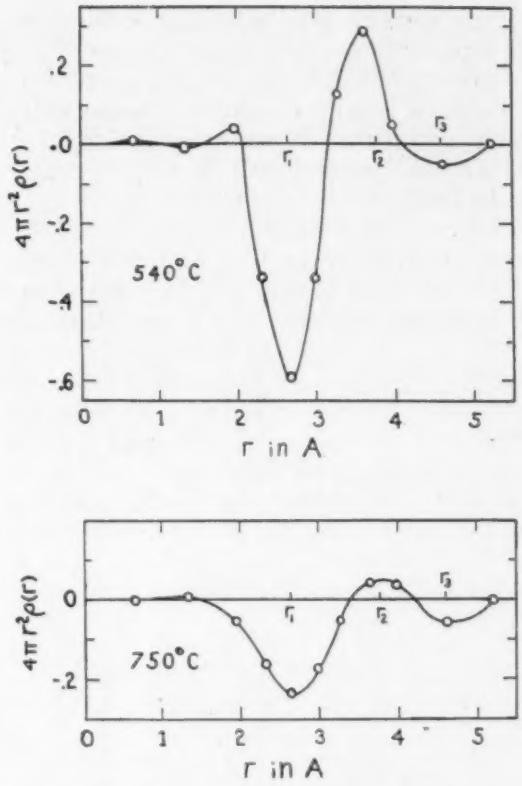

FIG. 7. Result of Fourier integral analyses of the curves I_{SRO}, Fig. 6. The interatomic distances r_1, r_2, and r_3 are indicated.

In Fig. 4 are the photographs used in the study of short range order and in Fig. 5 are their respective microphotometer traces. In each case the 200 line was attenuated by a factor of 0.251 so that its integrated intensity could be conveniently measured. The method employed to measure the background intensity can be outlined most easily with the help of the following equations.

$$I_{B(\text{abs})}=I_B\frac{I_0e^4N}{m^2c^4R^2}\frac{1+\cos^2 2\theta}{2}\frac{a}{\mu}\times\frac{\sin\phi\sin(2\theta-\phi)}{\sin\phi+\sin(2\theta-\phi)}=KI' \quad (19)$$

and

$$P_{200}=K\int_{200}I'dx, \quad (20)$$

where $I_{B(\text{abs})}$ is the total background in absolute units, I' is the intensity in arbitrary units obtained from the microphotometer trace, K is the appropriate constant of proportionality whose value need not be known, P_{200} is given by Eq.

(7), x is the equatorial distance *on the film*, and the integral is taken between values of x associated with the 200 line. From the above equations, I_B is readily obtained in terms of measurable quantities. Furthermore, since I_R, I_C, and I_T can be computed, it follows that I_{SRO} can be evaluated by Eq. (13).

The quantities I_B, I_C, I_T, I_R, and I_{SRO} are shown graphically in Fig. 6. For the ordered sample the total background is just the sum of the Compton modified and temperature diffuse scattering. Fourier integral analyses were performed on the curves I_{SRO} using the methods proposed by Danielson and Lanczos,[9] the results of the analyses being shown in Fig. (7). Values of σ_i were obtained in accordance with Eqs. (18a) and (18b). A summary of the experimental results for short range order is given in Table II.

TABLE II. Experimental results for short range order.

Temperature	ϕ	$\overline{u^2}$	σ_1	σ_2	σ_3
750°C	13.3°	0.030	0.25	0.05	0.03
540°C	10.7°	0.040	0.50	0.13	0.03
(Ordered)	11.15°	0.011			

DISCUSSION

Comparison of experiment with theory for long range order, Fig. 2, shows that the experimental results are in somewhat closer agreement with Peierls' theory than with Bragg and Williams' theory. However, in view of the preliminary nature of the experiment, it is not possible to judge adequately any of the theories.

The experimental results for short range order are in general agreement with theory. In each case the background intensity was adequately accounted for, and the degree of short range order was found greater for 540°C than for 750°C. It can be seen that the maxima and minima of the curves $4\pi r^2\rho(r)$ (Fig. 7) occur very nearly at r_1, r_2, and r_3, the interatomic distances, and that the necessary condition $\sigma_i > 0$ is fulfilled in each case.

These experiments on order should be regarded as being of an exploratory nature and not necessarily very accurate as to the numerical values obtained. They do indicate, however, that the methods proposed are valid and feasible. With refinements in experimental technique, one should be able to obtain reliable results for both long range order and short range order.

ACKNOWLEDGMENT

The writer wishes to express his indebtedness to Professor B. E. Warren for suggesting this research and for his help on the various problems which arose in the course of the investigation. Also, thanks are given to Dr. S. Siegel of the Westinghouse Research Laboratories for the excellent samples of Cu_3Au used in these experiments.

APPENDIX

Absorption Correction for Flat Samples

Let P_0 be the integrated intensity per unit volume on the basis of no absorption. Then from Fig. 8 we see that

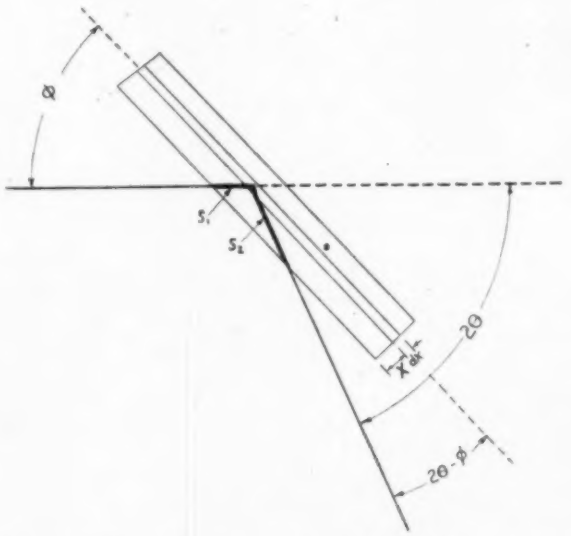

FIG. 8. Diffraction of x-rays by reflection from a plane opaque powder sample.

the diffracted power contributed by the elemental slab dx is $dP = P_0 \exp(-\mu\{s_1+s_2\})dV$. The elemental volume $dV = a\,dx$, $s_1 = x/\sin\phi$, $s_2 = x/\sin(2\theta-\phi)$, hence

$$P = aP_0\int_0^\infty \exp\left(-\mu x\frac{\sin\phi+\sin(2\theta-\phi)}{\sin\phi\sin(2\theta-\phi)}\right)dx$$

$$= P_0\frac{a}{\mu}\frac{\sin\phi\sin(2\theta-\phi)}{\sin\phi+\sin(2\theta-\phi)}.$$

The tacit assumption made that the sample contains no interstices between the crystal particles does not alter the final result in this case.

A New Experimental Approach to the Study of Boundary Lubrication

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(Received August 4, 1944)

A description is given of apparatus for measuring the relative ability of rubbed-down monolayers of polar lubricants to maintain low friction under test conditions which do not permit replacement of the lubricant. This quality of a lubricant is called its "durability." The clean polished rim of a slowly rotating steel wheel rubs on the monolayer deposited on a polished steel flat. An account is given of the preparation of the surfaces and films. It was not found possible to prepare reproducible test surface-monolayer combinations, hence it was necessary to compare each lubricant with a standard deposited on a separate area of the same surface. Significant differences are found in the relative durabilities of a number of polar compounds. For the monocarboxylic acids tested, the values are found to increase with the number of carbon atoms per molecule. An investigation of the stability of rubbed-down monolayers on polished stainless steel shows that aging in a desiccator causes a continuous decrease in durability, and also a decrease in molecular orientation as shown by electron diffraction. Similar reduction of durability and orientation results when the film is flushed with a fine stream of benzene. On chromium also the orientation is destroyed by the solvent, but the durability is not changed.

INTRODUCTION

WHEN two lubricated surfaces slide over each other, one can always choose high enough values of the pressure between them, and low enough values of the relative sliding speed, to make it impossible for a truly fluid film of the lubricant to form. The term "boundary lubrication" applies to the condition in which the lubricating film is not thick enough to prevent contact between the rubbing surfaces. It differentiates between "fluid-film" or "hydrodynamic" lubrication, and the condition in which the surfaces are so close together as to influence directly the physical properties of the lubricant. In fluid film lubrication, viscosity is the only property of the lubricant which affects the frictional forces. In boundary lubrication, the frictional forces are essentially independent of viscosity. For a recent review of boundary lubrication see Beeck.[1]

Inasmuch as boundary conditions are encountered in one form or another in almost all lubrication problems, the study of boundary lubrication has been considered of great importance for many years. Boundary lubrication conditions are most easily obtained in laboratory tests by using, as one rubbing member, a slider (usually rounded or hemispherical) that penetrates the lubricating film. This principle has been employed in practically all investigations. Recent examples are Langmuir,[2] Claypoole,[3,4] and Bowden *et al.*[5,6]

[1] O. Beeck, J. App. Phys. **12**, 512 (1941).
[2] I. Langmuir, J. Frank. Inst. **218**, 143 (1934).
[3] W. Claypoole, Trans. A. S. M. E. **61**, 323 (1939).
[4] W. Claypoole, Trans. A. S. M. E. **65**, 317 (1943).

LUBRICANT DURABILITY

The investigation of the action of lubricants in boundary lubrication may be divided arbitrarily into two phases:

1. *The measurement of the coefficient of friction during sliding under conditions which permit replacement or redistribution of the used lubricant.* Such conditions are encountered when the smaller of two rubbing surfaces is in continuous moving contact with a larger surface, which carries the test lubricant. The smaller surface continuously moves into a lubricated area of the other rubbing surface, and picks up, carries along, and redistributes lubricant from the areas over which it passes. The conditions governing this replacement are determined predominantly by the mechanical arrangement of the apparatus, and only slightly by the properties of the lubricant.

2. *The measurement of the coefficient of friction under conditions which permit essentially no replacement or redistribution of the used lubricant.* Such conditions are encountered when lubricant not more than a few molecular layers thick is carried by the smaller of two rubbing surfaces and no lubricant is carried by the larger. If the mechanical arrangement does not permit previously used regions of the larger surface to come into contact with the lubricated surface, the test will measure a unique quality of the lubricant.

This paper is concerned exclusively with a study of the second phase. The property of a

[5] F. P. Bowden and L. Leben, Proc. Roy. Soc. **A169**, 371 (1939).
[6] F. P. Bowden and L. Leben, Phil. Trans. **239**, 1 (1940).

boundary lubricant which enables it to keep the coefficient of friction low under these conditions is called by us its "durability."* A more exact definition is given below. Because of the mobility of the molecules in a lubricating film even as thin as a few molecular layers, the second phase can be experimentally realized most satisfactorily by use of a lubricant film of the order of one molecule thick. A new apparatus which has been developed specifically for the investigation of the lubricant durability problem is described. Some of the results obtained on the durability of very thin films are presented and some interesting and apparently new properties of monolayers of polar lubricants are discussed.

THE LUBRICANT DURABILITY APPARATUS

Figure 1 is a simplified schematic diagram of the lubricant durability apparatus, showing only its essential elements. The clean, polished rim of a slowly rotating steel "friction wheel" is one rubbing member, and a small flat steel "test specimen" is the other. A monomolecular layer of the lubricant to be tested is deposited on the lower face of the test specimen by a method to be described later.

When in position, the test specimen forms part of a rigid balance assembly to which are fastened two diamond hemispheres which bear on glass microscope slides. When the assembly is balanced in a horizontal position by adjusting the movable weight at its right end, the face of the test specimen just touches the upper edge of the rim of the friction wheel. Any weight subsequently added to the balance assembly directly above the point of contact between the wheel and the specimen constitutes the entire load on the lubricant film. This load has been chosen to be 100 grams.

The direction of rotation of the wheel, whose angular speed is 1/30 r.p.m., is such that the frictional force between it and the specimen tends to drag the whole balance assembly toward the left in Fig. 1. Movement of the assembly is prevented only by the frictional force of its diamond supports on the glass slides. This frictional force determines the maximum coefficient of friction between the friction wheel and the test specimen.

If the diamond-on-glass frictional force is larger than the initial frictional force between the friction wheel and the test specimen, the balance assembly does not move when the rotation of the wheel is started. For a certain period, therefore, the rim of the friction wheel continues to rub against one small area of the test specimen. This wiping action of the clean rim slowly wears off lubricant and carries it out of that area, causing the frictional force there to rise continuously. In a very short time it reaches the value of the diamond-on-glass frictional force. At that instant the diamonds slip, and the contact region on the test-specimen shifts.

If the test were stopped at this point, the total angle of rotation of the friction wheel would serve as a measure of the ability of the lubricant initially present in the rubbing area to resist removal and to maintain the frictional force there below the diamond-on-glass value, i.e., to limit the coefficient of friction to a known value. However, the test would have been conducted on a very small area of the test specimen surface, and the angle of rotation of the friction wheel would likewise be small, so that the sensitivity and reproducibility would be poor.

If the test is allowed to proceed, however, slip of the diamonds allows the test specimen to move forward and place a fresh area of its lubricant-covered surface in contact with the moving rim of the friction wheel. The frictional force then drops below that between the diamonds and the glass, and slip between the wheel and the specimen occurs once more. The cycle just described may be repeated continuously until the test specimen has been dragged through any desired distance, provided that the wheel has not made a complete rotation. The angle of rotation for the entire test can then be used as a measure of the lubricant's durability, and the advantage of integrating or averaging the frictional phenomena over a track of considerable length on the test specimen is gained.

Obviously the wheel must not be used for more than one complete revolution before being repolished and cleaned, since the contamination picked up on its surface would then be fed back into the rubbing area. Normally, ten to twenty tracks of a convenient length, each equivalent to 10 degrees rotation of the wheel, can be tested within one revolution.

The durability is defined by the following equation:

$$d=\frac{\theta_2-\theta_1}{\theta_1}=\frac{S}{\theta_1}=\frac{\text{Slip}}{\text{Track length}}. \qquad (1)$$

* Claypoole, reference 3, has applied the term "wearability" to a boundary lubrication test which belongs to phase 1, above.

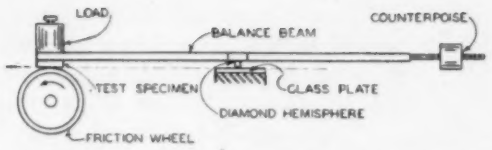


FIG. 1. Schematic diagram showing only the essential elements of friction wheel durability apparatus.

In Eq. (1), θ_2 is the wheel rotation (degrees) with the lubricant present, and θ_1 is the wheel rotation (degrees) with no slip between the wheel and the test specimen, i.e., θ_1 is the track length expressed in degrees. The difference $\theta_2 - \theta_1 = S$ is called the slip. It is obvious that d depends upon the frictional force between the diamond supports and the glass slides, increasing as this force increases. A convenient value for this force, namely, 20 grams, has been chosen in most experiments, so that the maximum coefficient of friction between the friction wheel and test specimen is usually 0.2.

EXPERIMENTAL DETAILS

Figure 2 is a schematic drawing showing details of the apparatus. The test specimen (A) is a 15-mm square stainless steel interferometer mirror,* which was selected because of its ability to take a very high polish. Its hardness is tempered to about 400 diamond Brinell. The square, sharp-edged, longitudinal slot divides the face of the test specimen into two equal areas which are used in making the relative durability measurements described below. The test specimen slides in dovetailed ways provided in the specimen holder (B) of the balance assembly (C). A metal tab (D) soldered to its top face serves as a holder during cleaning and as a bearing for an adjustment screw (E).

The friction wheel (F) is made of S.A.E. 52–100 steel, and has a hardness of about 800 diamond Brinell. Its diameter is $1\frac{3}{4}$ inches and the shape of its rim is shown in cross section (G) on Fig. 2. The cusps have an important function which will be described later. The friction wheel is fitted on a steel shaft supported on preloaded ball-bearings in a mount that can be detached from the apparatus, as shown on Figs. 3 and 4. All wobble of the vertex of the rim, which has a radius of curvature of 0.015 inch, is removed by grinding under a microscope while the friction wheel is driven in its own mounting. It is extremely important that the surface of the wheel be very clean and highly polished, so that final shaping, polishing, and cleaning of the rim are done just prior to each use of the wheel.

From the time it is cleaned in preparation for a series of tests, and until the tests have been completed, the friction wheel is enclosed in a transparent plastic housing (shown in Fig. 4) through which is circulated a dry inert atmosphere. An inverted plastic trough is used to

* Obtained from the Gaertner Scientific Corporation, Chicago, Illinois, with an initial hardness of 665 diamond Brinell.

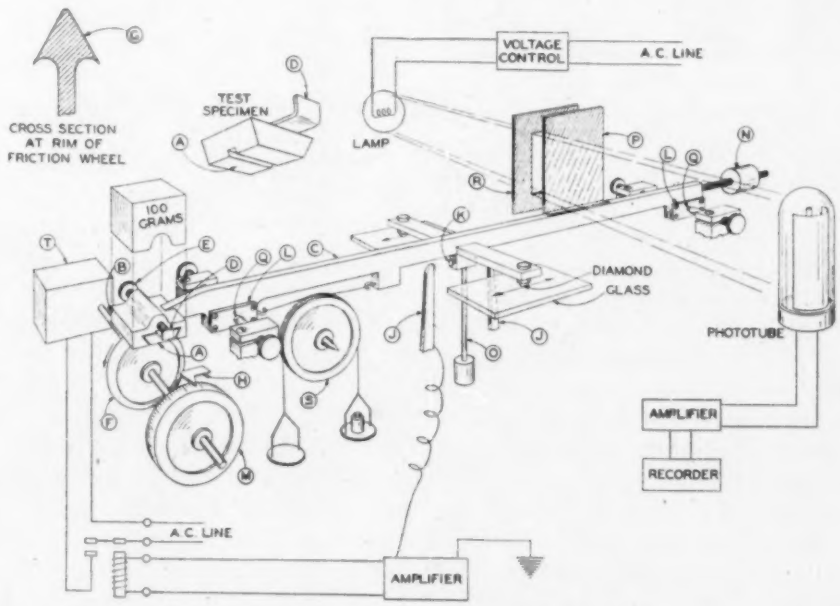


FIG. 2. Schematic diagram of friction wheel durability apparatus.

protect the exposed tip of the friction wheel rim from contamination during adjustment of the test specimen. During operation, and for 30 minutes prior to starting a series of tests, both the test specimen and the tip of the friction wheel rim are enclosed in a third plastic case. A clean dry atmosphere was found essential. The test is particularly sensitive to contamination of

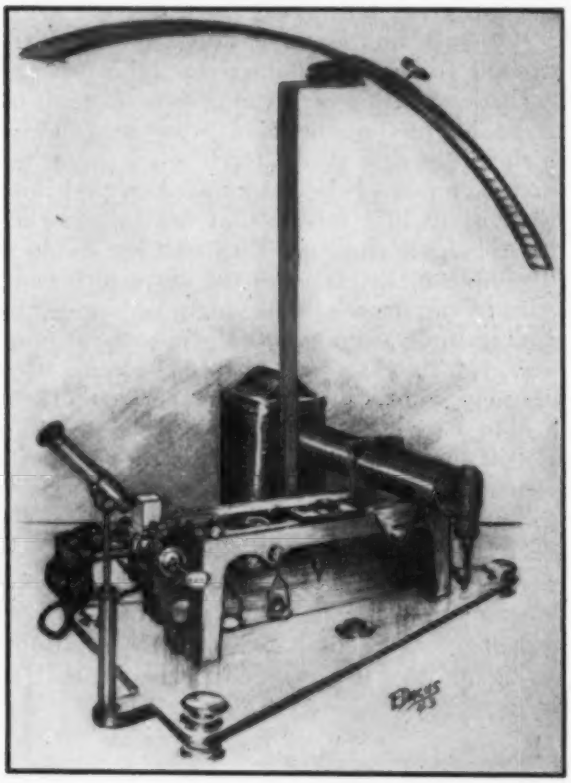


FIG. 3. Friction wheel durability apparatus.

the surface of the wheel rim by the laboratory air and to variations in the humidity of the atmosphere surrounding the test film.

The angle of rotation of the friction wheel is measured by means of the telescope, mirror, and scale shown on Fig. 3. The mirror is locked to the wheel shaft by its knurled thumb-screw handle, and can be set to give a zero reading on the scale before each test. The curved scale is graduated in one-half degree divisions, and readings are estimated to 0.1 degree.

An indexing wheel (M), having 100 equally spaced divisions around its rim, slips on and is locked to the friction wheel shaft outside the wheel mount (see Figs. 2 and 3). A fixed pointer (H) shown on Fig. 2 makes it possible to record for future reference the particular arc of the friction wheel rim which is used in each test.

The wheel mount slides into lateral ways on a carriage which is adjustable vertically by means of a rack and pinion. The fine lateral adjustment required for accurate alignment of the friction wheel rim with the central plane of the balance beam is provided by a micrometer head. The carriage supports a Telechron motor (T) with reducing gears to drive the shaft of the friction wheel at a speed of 1 revolution in 30 minutes. The peripheral speed of the wheel is 0.183 inch per minute.

Adjustable stops (J) limit the travel of the balance assembly and determine the length of the test tracks. They are adjusted so that the total track length corresponds to a wheel rotation of 10.0 degrees. When the contact (K) on the balance assembly touches the left-hand stop in Fig. 2, the amplifier causes the relay to open the driving motor circuit, automatically stopping the test.

As shown in Fig. 2, the balance assembly consists of the specimen holder (B), the guide plates (L), the diamond-glass friction device, a counterpoise (N), a weighted vertical member (O) for lowering its center of gravity, and a metal shutter (P). All longitudinal forces on the balance assembly act horizontally in the plane of the specimen surface.

The specimen holder has horizontal ways into which the test specimen slides, and in which it can be locked. The lateral position of the test specimen in the holder is controlled by an adjustable thumb-screw (E), which makes possible the repetition of the durability test on a large number of closely spaced parallel tracks on its surface.

It is important that there be no lateral motion of the balance assembly during test. To accomplish this while keeping frictional forces negligible, use is made of four adjustable diamond-button guides (Q) which bear lightly on four polished hardened steel guide plates (L) fastened to the sides of the balance beam. These guide plates are surface ground in place on the balance beam in order to insure that their faces are parallel. Diamond was selected for the button material because of its low coefficient of friction on unlubricated polished steel which previously had been established in this laboratory (Claypoole).[3] For precise adjustment of the guides, the balance beam is suspended by fine threads, and the positions of the diamond buttons are

adjusted so that the balance beam will just swing freely between them.

The diamond-on-glass friction device is an essential feature of the apparatus. Its function is to limit the coefficient of friction between the friction wheel and the test specimen to a predetermined maximum, without causing any motion of the test specimen. While a variety of limiting methods could be used, the last condition can be met only by a system in which some form of frictional force is predominant.

The diamond hemispheres attached to the balance beam rest on glass microscope slides set in a Bakelite block on the frame of the apparatus (see Figs. 2 and 3). The diamond-on-glass combination was selected because of its especially uniform coefficient of friction, which was established by a series of separate tests. This uniformity is increased if the surface of the glass is run in by sliding the diamonds back and forth a few times under an increased load, and is maintained by flooding the glass surfaces with white medicinal oil.

The value of the frictional force opposing the motion of the test specimen is measured by means of the pulley and weight system (S) shown in Fig. 2. Any compensating adjustments necessary to maintain the total limiting force at a chosen value are made by the same system.

From the constant test load of 100 grams and the known radii of curvature of the friction wheel, it has been calculated by use of the Hertz theory that the maximum pressure in the rubbing area is 130,000 p.s.i.

If the test specimen and friction wheel surfaces are uniform, and if the lubricant film is uniform, the test specimen will be moved along by the friction wheel at a sensibly uniform rate. Actually, the motion of the test specimen proceeds in jerks, but these jerks are so small and so frequent that careful observation under a microscope is necessary to note them. If the friction wheel or the test specimen surfaces are non-uniform and if contamination of any sort is present to change the rate of motion of the test specimen, the observed durability will be incorrect. In general, such a change is not detectable by visual observation, because the specimen motion is too slow. Therefore, in order to determine the nature of the motion executed by the test specimen, a photoelectric device for recording its travel is used.

The principle of the photoelectric device, which is indicated schematically in Fig. 2, and whose housing is shown at the right of Fig. 3, is extremely simple. One of the essential features is that it does not affect the motion of the balance beam. A shutter (P) attached to the balance beam intercepts an increasing fraction of the light passing through a fixed rectangular opening (R) as the beam moves forward, and so varies the amount of light that falls on a photo-tube. Unchanging distribution of the light over the photo-tube is accomplished by a lens (not shown in Fig. 2) at the shutter. Variations in the output of the photo-tube are amplified, and recorded by a "Micromax" recorder. Electronic voltage control is provided for the d.c. light source. Since the friction wheel and the chart of the Micromax are driven at constant rates, length along the chart represents angular rotation of the friction wheel.

This recorder has proved invaluable. A satis-

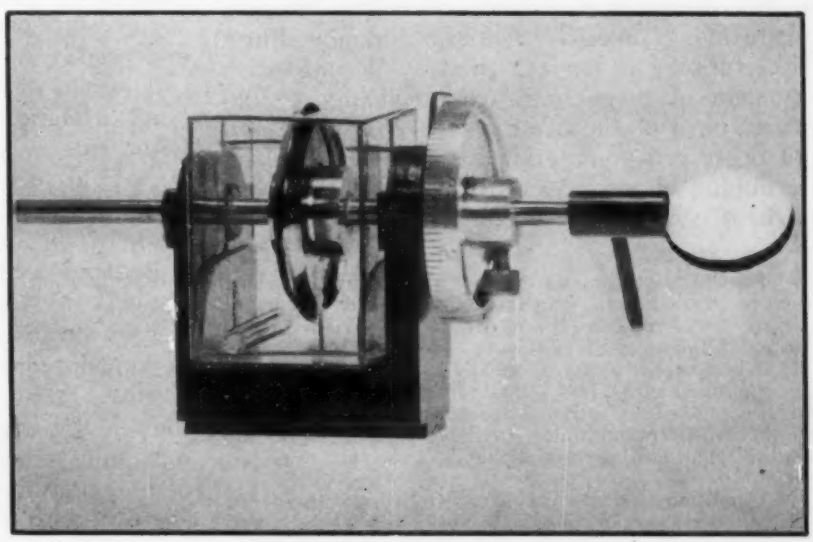


FIG. 4. Friction wheel—mount and case.

factory test is indicated by a straight line on the record. The presence of local breaks or jogs in a straight line indicates that lint or particles of dust or other foreign matter have interfered. Such a test will usually be satisfactory when corrections are applied for the breaks. A curved line indicates a non-uniform distribution of lubricant, or faulty surface conditions, and the test must be discarded.

PREPARATION OF TEST SPECIMEN

The surface of the test specimen is prepared by lapping, polishing, and cleaning before the deposition of each new test film. If any considerable portion of its surface is badly scored, the specimen face is first surface ground with a fine stone. Lapping is done by hand on a flat solder pad whose surface is especially grooved and is charged with 303½ M optical emery.*

The specimen is polished with optical rouge and water, on "kitten's-ear" broadcloth which is stretched on plate glass. Long even strokes in one direction only are used, thus keeping the nap flat and producing an unruffled polish. If the surface has been properly lapped, all visible lapping marks will disappear after 50 to 100 ten-inch polishing strokes. 300 such strokes were adopted as a uniform standard. A very high state of polish is obtained. Emphasis is placed on the absence of scratches, and not upon the flatness of the surface.

It is important that the test specimen be completely free of all greasy and abrasive material. To accomplish this, it is essential that rubber gloves** which have been cleaned in chromic acid and flushed with a high grade of distilled water be worn during the entire cleaning operation. The greasy material is removed first by scrubbing all parts of the test specimen with a paste of magnesium oxide (Shamva†) and water on a clean cotton swab. This paste and all other gritty material are then removed by scrubbing all surfaces with clean swabs of absorbent cotton while flushing them in a stream of boiling hot distilled water from a wash bottle. The test specimen is held by its metal tab with chromium-plated tweezers. The tweezers and the cotton swabs used for this operation are first cleaned by boiling them in an Erlenmeyer flask filled to the brim with distilled water. The water is allowed to boil over in order to remove any greasy material which has collected on its surface. After the specimen has been swabbed and flushed with hot distilled water, most of the water is flicked off and the remainder dries almost immediately. Cleaning must be repeated if there is any tendency for the thin film of water remaining after flicking to draw up into droplets on the surface. The lubricant films to be tested are deposited immediately on the test specimen, thus permitting a minimum of exposure of the test specimen surface to the laboratory atmosphere.

Preparation of the Friction Wheel

All operations necessary to the preparation of the surface on the friction wheel rim are carried out with the wheel mount fastened at the edge of the laboratory sink, where the wheel is driven at about 100 R.P.M. by a small motor. A 30-power binocular microscope is focused on the rim to observe the results during all stages of the preparation. The radius of curvature of the rim cross section, approximately 0.015 inch, is frequently checked during the preparation by projecting, through a low power microscope, a profile image of the rim against a calibrated curve under standard projection conditions. It has been found essential to keep this radius of curvature uniform and reasonably constant, in order that the pressure on the lubricant film shall not vary appreciably.

The rim of the friction wheel is shaped by hand, using a fine flat Arkansas stone kept wet with water and in constant sidewise motion. Very light pressure is used and the operation is continued until all but the finest scratch marks made by the stone itself have been removed.

Before polishing, the rim is lapped with 303½ M optical emery on a small pad of absorbent cotton wet with water. It is essential that this pad also be kept in constant sidewise motion to prevent scoring. The operation is continued until only the fine scratches left by the emery remain. All remaining emery is scrubbed off the surface before polishing. The polishing operation is identical with the lapping operation, except that

* The special technique involved in making and using such pads, used in the preparation of optically flat metal surfaces, was obtained from Mr. W. E. Webb of the National Bureau of Standards.

** Clean rubber gloves should be worn during lapping and polishing also. The "stars" frequently encountered when stainless steel surfaces are polished with rouge are eliminated by maintaining extreme cleanliness of the materials and tools used in all stages of the surface preparatioh.

† A polishing powder made by Golwynne Magnesite and Magnesia Corporation, New York, New York.

chromium oxide on broadcloth is used instead of emery on cotton.

The success of the lubricant durability measurement is critically dependent upon the cleaning of the friction wheel. Since it is not possible to attain absolute cleanliness of the wheel's surface, it is important to reach a state which can be reproduced from one preparation to another. The prime requisites of this state are that no oily or abrasive contamination be present.

The following cleaning procedure has been found satisfactory. The friction wheel is driven at 200 R.P.M., while all surfaces, including the side walls and hub, are thoroughly scrubbed with Shamva applied in a thick paste on a clean absorbent cotton swab. This operation is accompanied by frequent flushing in a stream of hot distilled water from a wash bottle. All parts of the walls are painted with the paste, which is allowed to set up like plaster. It is then scrubbed off the rim only, using boiled cotton swabs and boiling hot distilled water. During the removal of the Shamva from the rim, the hard plaster on the side walls can introduce no contamination. A fork-shaped suction device is fitted around the lower edge of the revolving rim during the final stage of flushing and swabbing. Its openings extend from the vertex to just beyond the cusps of the rim, so that water on the side walls, which might otherwise be forced past the flared edge by centrifugal force, is prevented from reaching and contaminating the working area of the rim. The travel of the rim leads the flushing water and loosened particles immediately to the suction device, which removes them completely. Almost the instant that swabbing and flushing are stopped, the rim of the friction wheel becomes dry because of the suction and the evaporation of the very hot water that is used, but the side walls and hub will remain wet considerably longer. This presents no problem, however, since there is no tendency for the water to flow past the sharp edges of the cusps to the clean outer surface. Consequently no Shamva or greasy film on the water surface gets to the outer rim from the side walls.

STUDY OF THE RUBBED-DOWN MONOLAYERS

It is generally believed (Blodgett and Langmuir[7] and Germer and Storks[8]) that a compact monomolecular layer of a polar lubricant can be deposited on a reasonably clean polished metal surface if an excess of the lubricant is smeared over the surface and then rubbed with several changes of clean soft cloth or lens paper. It is also believed that all of the polar molecules that can be brought into intimate contact with the metal by this process will attach themselves to the surface so strongly that they cannot be removed by any amount of rubbing short of that which would abrade the metal, and that the excess molecules which are not directly attached to the metal will be so loosely held that they can be removed with relative ease. It is known that the film which is left has an optical thickness equal to that of a dipped layer produced by the Blodgett[9,10] dipping technique. Electron diffraction examination shows that the molecules in such a rubbed film are oriented normally to the surface (Germer and Storks[8,11]), and it is reasonable to suppose that rubbing in the presence of excess produces packing of the molecules. The rubbing technique is in general use (Blodgett and Langmuir[12]) for producing the first layer on which a polylayer film is subsequently built up by the Blodgett dipping method.

On the assumption that a close-packed monolayer of polar molecules could be produced by this rubbing-down method, and that such films should be reproducible from one experiment to another, this method was adopted for the preparation of the test film on the test specimen.

In a study of the durability of such films, fairly constant results were obtained over the several tracks that could be tested on a particular film. However, very poor reproducibility was found in experiments on separate surface-and-film preparations using the same lubricant. In the investigation of this problem, several phenomena were observed which indicated that the rubbed-down films did not have the stability and permanence which had been originally assumed.

The first indication that the rubbed-down films were not stable was furnished by the observation that the durability of a given film decreased materially with time of aging in a desiccator. Figure 5 shows typical curves of the durability

[7] K. B. Blodgett and I. Langmuir, Phys. Rev. **51**, 964 (1937).
[8] L. H. Germer and K. H. Storks, Phys. Rev. **55**, 648 (1939).
[9] K. B. Blodgett, J. Am. Chem. Soc. **56**, 405 (1934).
[10] K. B. Blodgett, J. Am. Chem. Soc. **57**, 1007 (1935).
[11] L. H. Germer and K. H. Storks, J. Chem. Phys. **6**, 280 (1938).
[12] K. B. Blodgett and I. Langmuir, Phys. Rev. **51**, 964 (1937).

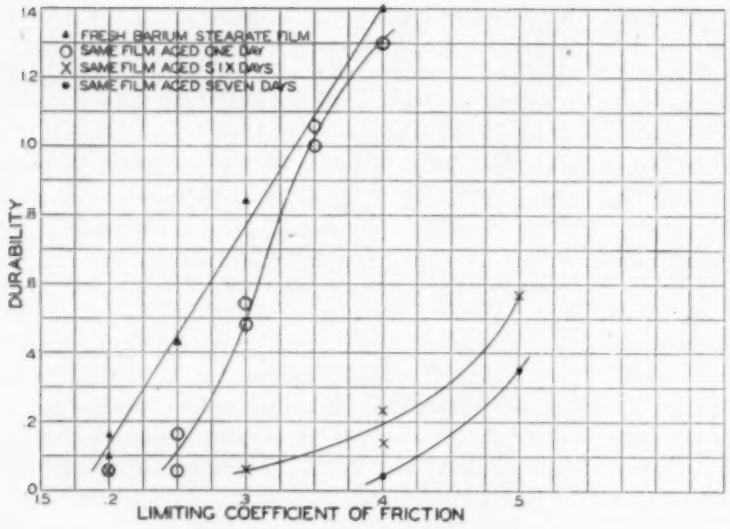

FRESH BARIUM STEARATE FILM
SAME FILM AGED ONE DAY
SAME FILM AGED SIX DAYS
SAME FILM AGED SEVEN DAYS
DURABILITY
LIMITING COEFFICIENT OF FRICTION

FIG. 5. Effect of aging on the durability of a barium stearate monolayer.

of barium stearate as a function of the maximum coefficient of friction permitted during a run. It will be noted that the durability corresponding to a given maximum coefficient of friction decreased materially as the film aged over a period of one week.

Further information about the effect of aging on the rubbed-down monolayers was obtained by an electron diffraction examination. The results are shown in Fig. 6. Figure 6(a) shows the diffraction pattern obtained on a freshly rubbed-down monofilm of barium stearate. It will be observed that the diffraction bands are nearly straight, and are parallel to the edge of the shadow of the test specimen. Diffraction photographs obtained by the same technique have been published by Germer and Storks,[8,11] who have pointed out, in agreement with Murison,[13] that the spacing of the bands corresponds to the distance of 2.50A between alternate carbon atoms in the flat zig-zag structure of the barium stearate molecule, and that the straight bands indicate orientation of the molecules with their long axes normal to the supporting surface. It was estimated by Germer and Storks that the very slight curvature of the bands shows that the axes of the hydrocarbon chains deviate from the surface normal by less than approximately 10 degrees. The uniform intensity within the bands shows that there is little if any regularity of lateral arrangement of the molecules.

The increased curvature and decreased intensity of the diffraction bands shown in Fig. 6(b) show that many of the molecules were no longer standing normal to the surface after the film had aged for three days. In a similar manner, the two diffuse arcs visible in Fig. 6(c) are taken to represent the random orientation of the hydrocarbon chains in a film aged for seven days. Patterns similar to those shown in Fig. 6(c) have been observed by Plessing[14] for the clean surface of a polished metal, but the radii of the arcs of his metal patterns do not agree with the radii in Fig. 6(c).

These results appear to associate the observed reduction in durability after aging of the film with a transformation from a close-packed oriented state to a state of random orientation. This may occur as a result of a change in the metal surface caused by oxidation or corrosion on an extremely minute scale. Such a change would naturally also affect the observed durability values, and indeed may be the chief cause of their decrease with aging of the test film. It is certain that evaporation of the barium stearate is too slow to account for this decrease. Although a completely satisfactory explanation of the observations is not possible on the basis of the experimental work done, it is certain that the rubbed-down monolayer is not so stable a film as was supposed.

It was believed that a monolayer of polar molecules could not be removed from a metal surface by use of a solvent, the attraction of the polar groups for the metal surface being con-

[13] C. A. Murison, Phil. Mag. [7] **17**, 201 (1934)

[14] E. Plessing, Physik. Zeits. **39**, 582 (1938).

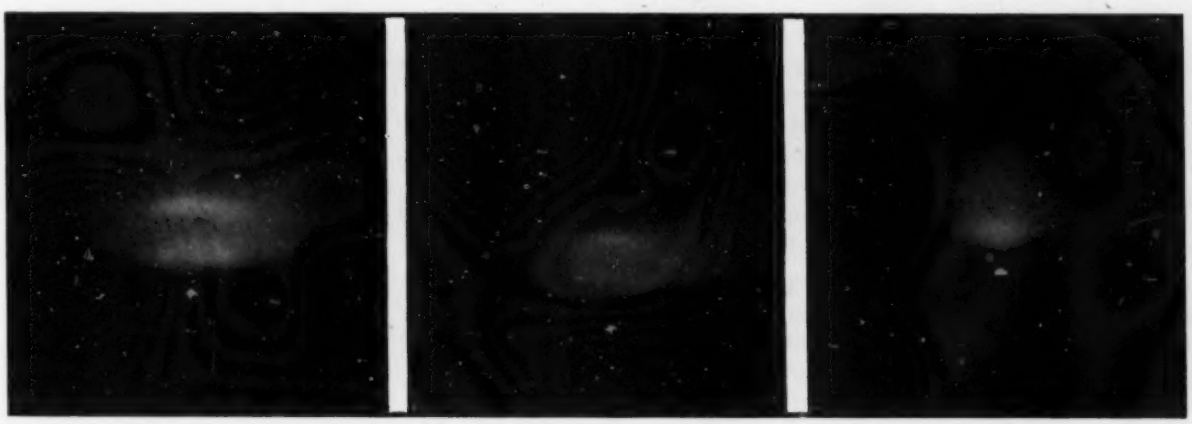
sidered to be too great.* In order to test the validity of this conception, the durability of films of barium stearate on stainless steel was measured after a variety of treatments with benzene. It was found that a film of barium stearate which had been rubbed down to a monolayer by the normal procedure had almost zero durability after it was swabbed lightly with cotton dipped in benzene. Similarly, it was found that repeated flushing of a rubbed-down film of barium stearate for about 20 seconds in a fine stream of benzene caused a progressive decrease in durability. After the third flushing the durability was nearly zero. Similar results were obtained on sebacic acid, oleic acid, and stearic acid. In all cases electron diffraction examination showed that the original typical oriented monolayer pattern had changed to an unoriented pattern similar to those shown in Fig. 6, (b) and (c), after the first flushing. This definitely proves that the flushing with benzene at least destroyed the orientation of the monolayer. It seems probable on the basis of the durability results that an appreciable number of barium stearate molecules were removed from the metal surface, but the electron diffraction examination does not prove this.

Similar tests were made using barium stearate on a thickly chromium-plated steel surface. It was found that repeated flushing with benzene did not reduce the durability. This seemed to indicate that the lubricant had not been removed from the chromium surface, but electron diffraction examination failed to detect the presence of an oriented film after the first flushing. Under the microscope the chromium surface was seen to be covered with fine shallow criss-crossing rounded grooves. It is possible that the results on the chromium-plated surface were caused by the storage of lubricant in these irregular microscopic grooves. This postulate was supported when it was found that the type of diffraction pattern usual for an oriented monolayer returned when a film that had been previously flushed was later rubbed down with dry cotton. This suggested that the rubbing process drags lubricant out of the valleys in the surface and distributes it over the rounded hills where it can be "seen" by the electron beam. Likewise, the rubbing action of the friction wheel might move it out where it could increase the durability.

All of the results described above show that a rubbed-down monolayer of a polar lubricant is not so stable and permanent as had been supposed.

On the other hand, an investigation showed that variations in the amount and severity of rubbing of barium stearate monolayers caused no significant differences in durability values. Similar findings resulted when more of the same lubricants was rubbed on. Representative data are given in Table I. These results demonstrate the extreme stability of the rubbed-down monolayer against rubbing, in confirmation of the concepts mentioned at the beginning of this section.

* Germer and Storks (reference 8) showed that dipping a 7-layer Blodgett-type film of barium stearate in benzene did not change its electron diffraction pattern. We have found no discussion in the literature of the action of benzene on a rubbed-down monolayer of barium stearate, but one would expect it to have a smaller effect than on a polylayer film.



(a) (b) (c)

FIG. 6. Electron diffraction photographs showing the relationship between aging and molecular orientation in a barium stearate monolayer on stainless steel: (a) fresh barium stearate monolayer, (b) same monolayer three days old, (c) same monolayer seven days old.

TABLE I. Showing the small effect of consecutive variations in the rubbing treatment on the durability of a barium stearate film-surface combination. The coefficient of friction was limited to 0.35 and one wheel preparation sufficed for this series of tests.

(1) Fresh film rubbed moderately	(2) Rubbed severely	(3) Ba.st. added rubbed moderately	(4) More Ba.st. rubbed moderately
1.00	1.02	1.22	1.32
1.25	0.89	1.18	1.21
1.31	0.91		
1.19	0.94	1.20	1.27

RELATIVE LUBRICANT DURABILITY

The foregoing results show that neither variation in rubbing nor in amount of lubricant applied can account for the wide differences that are found (cf. Table II) between different film-surface preparations of the same lubricant. Hundreds of experiments on the preparation of the test specimen and friction wheel surfaces were performed in a vain attempt to determine the causes of this poor reproducibility. Finally, a test method was devised in which this reproducibility was not essential.

The test adopted is based upon the idea of relative durability, according to which one lubricant is taken as a standard and all other lubricants are compared with it. It is obvious that such a method will not be satisfactory unless all test conditions affecting the standard lubricant and the test lubricant are the same in any one test. It was necessary to devise a method of giving the two metal test surfaces identical treatment during their preparation, and also of giving the two films themselves identical treatment during the rubbing-down process. This was accomplished by depositing the films on separate areas of the same test surface, so that they could be rubbed down at the same time on the same metal. To prevent intermixing of the two lubricants, a shallow rectangular slot (about $\frac{1}{16}'' \times \frac{1}{16}''$) was cut across the center of the test specimen (cf. Fig. 2), thus dividing its surface into two equal areas. Since a drop of liquid will not readily flow past a sharp edge, drops of the lubricants can be deposited separately on each of these areas without danger of mutual contamination. Both films are then rubbed down simultaneously on successive clean pads of Kleenex tissue, using strokes parallel to the slot.

The value of the relative durability of a test lubricant is obtained by measuring two "abso-

TABLE II. Durability values—coefficient of friction limited to 0.20.

Test lubricant	Absolute durability: Test material	Absolute durability: Ba stearate	Relative durability
Group I—Monocarboxylic acids			
(a) Liquid at test temperature			
n-Butyric acid	0.52		
$CH_3(CH_2)_2COOH$	0.51	2.44	
	0.60	2.38	
	0.62	2.44	
	0.56	2.42	0.23
n-Caprylic acid	1.00		
$CH_3(CH_2)_6COOH$	0.94	1.96	
	1.04	1.78	
	0.92	1.76	
	0.98	1.84	0.53
Pelargonic acid	1.32	1.72	
$CH_3(CH_2)_7COOH$	1.20	1.72	
	1.16	1.58	
	1.21	1.65	
	1.22	1.65	0.74
(b) Solid at test temperature			
Lauric acid	0.98	1.33	
$CH_3(CH_2)_{10}COOH$	0.88	1.52	
	0.84	1.58	
	0.90	1.48	0.61
Myristic acid	1.65	1.88	
$CH_3(CH_2)_{12}COOH$	1.68	1.90	
	1.72	1.80	
	1.68	1.86	0.90
Palmitic acid	2.13	2.15	
$CH_3(CH_2)_{14}COOH$	2.16	1.99	
	2.15	2.07	1.04
Stearic acid	2.42	1.85	
$CH_3(CH_2)_{16}COOH$	2.50	1.70	
	2.46	1.78	1.38
Group II—Dicarboxylic acids			
Malonic acid	1.60	1.60	
$COOHCH_2COOH$	1.88	1.52	
	1.74	1.56	1.11
Suberic acid	0.35	1.59	
$COOH(CH_2)_6COOH$	0.29	1.61	
	0.32	1.60	0.20*
	0.22	1.70	
	0.18	1.69	
	0.20	1.70	0.12

TABLE II.—(*Continued.*)

Test lubricant	Absolute durability: Test material	Absolute durability: Ba stearate	Relative durability
Group III—Tricarboxylic acids			
Tricarballylic acid	0.36	0.70	
$HOOCCH_2CH(COOH)$-	0.38	0.68	
CH_2COOH	0.41	1.00	
	0.50	0.74	
	0.41	0.78	0.53*
Group IV—Salts and esters			
Sodium malonate	0.34	0.55	
$CH_2(COONa)_2$	0.30	0.55	
	0.27	0.55	
	0.32		
	0.31	0.55	0.56
	0.92	1.18	
	0.92	1.18	
	0.92	1.18	0.78
	0.51	0.77	
	0.50	0.72	
	0.42	0.74	
	0.44		
	0.47	0.74	0.64
Calcium stearate	2.44	1.83	
$[CH_3(CH_2)_{16}COO]_2Ca$	2.32	1.86	
	2.38	1.85	1.24
n-Propyl formate		1.08	
$HCOOC_3H_7$	0.80	1.00	
	0.78	1.00	
	0.86	1.03	
	0.86	0.96	
	0.82	1.01	0.81
	1.35	1.67	
	1.21	1.50	
		1.52	
	1.28	1.56	0.82
n-Propyl adipate		1.14	
$[(CH_2)_2COOC_3H_7]_2$	0.86	1.17	
	0.86	.90	
	0.86	1.07	0.80

* Approximate value—slip very erratic.

lute" durabilities, one on the standard lubricant and one on the test lubricant, and then taking the ratio of the latter to the former. Expressed by an equation the relative durabilities:

$$d_r = \frac{d_{test}}{d_{standard}}. \qquad (2)$$

Barium stearate has been chosen as the standard lubricant. Each absolute durability is the mean of several durabilities determined on parallel tracks on the pertinent area of the test specimen.

The relative durability test method just described has several advantages:

1. The two test areas are part of the same test specimen and therefore very likely to be of the same composition, structure, and hardness.

2. Both areas are lapped and polished simultaneously, and are therefore much more likely to have the same degree of polish than would two separately prepared surfaces.

3. The two areas are cleaned and dried simultaneously and are very likely to have the same degree of cleanliness.

4. After the specimen has been placed in the apparatus, the films on the two areas are dried in exactly the same conditions and for the same period of time.

5. A specimen does not have to be removed during comparative tests on the two films.

It cannot be claimed that the simultaneous rubbing down of the two test films will produce identical orientation, structure, and density, since these qualities will be affected by the physical and chemical properties of the two lubricants. However, the results of a large number of tests made with the relative durability method show that, even though the durability of each test film varies materially from one film specimen preparation to another, a fairly constant value of the relative durability is obtained.

In Table II are collected durability data on a variety of test lubricants. All of the test lubricants were Eastman White Label (Eastman Kodak Company, Rochester, New York).

The data show that the test reproducibility from track to track on the same test specimen is good. They also show the wide variation in absolute durability which results when the same lubricant is tested on a series of different test specimen preparations. Note the large variations in the values for barium stearate (0.55 to 2.42) and for sodium malonate (0.31 to 0.92). The variation in relative durability for a given material is much less, e.g., 0.56 to 0.78 for sodium malonate, 0.81 to 0.82 for *n*-propyl formate.

Figure 7 shows the relative durabilities of a series of monocarboxylic acids plotted against the number of carbon atoms per molecule. It will be noted that the relative durability increases

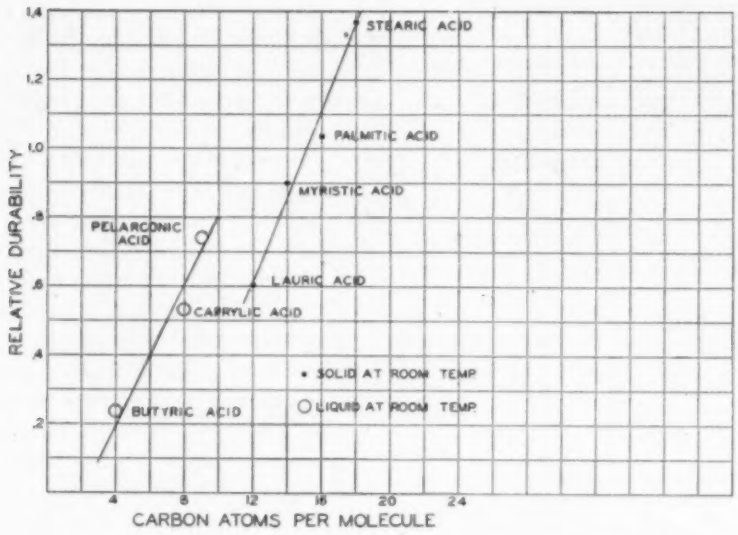


FIG. 7. The relative durabilities of monocarboxylic acids.

in approximate proportion to the length of the molecule. Analogous linear relationships for the coefficient of friction have been reported several times in the past (cf. Beeck[1]). It will also be noted that those acids which are liquid at room temperature (the test temperature) fall on one straight line, while those which are solid at the test temperature fall on another straight line having about the same slope as the first but displaced from it. A satisfactory explanation for this difference has not been found. It may be connected with the fact that the solid materials are applied to the test specimen in solution, and are then rubbed down in the solid state after the solvent has evaporated, while the liquids are applied directly and rubbed down from the liquid state. The increased relative durability of the liquid materials may result from failure to produce a true monolayer.

The authors wish to express their appreciation of the fine workmanship of Mr. Allan Jamieson, who built the apparatus in the laboratory shop.

Theory of the Multivibrator*

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(Received August 8, 1944)

The theory of the symmetrical multivibrator has been developed in a form which makes possible the computation of the period and the currents in the tubes in a relatively simple manner. The method is largely graphical. The behavior of the corresponding Eccles-Jordan trigger circuit is first determined and a "trigger" characteristic constructed, giving the values of the grid voltages of each tube when triggering takes place and the corresponding values of the currents in the tubes before and after triggering. From this characteristic, with slight changes, the operating conditions and the period of the multivibrator circuit are determined. It is found that the grid currents play an important part in determining these conditions and the period. The method was applied to an actual circuit and the computed values agreed well with the experimental results. The effect on the period and operating conditions of varying the parameters is discussed theoretically and the conclusions are compared with experiment.

THE multivibrator, a type of relaxation oscillator employing two triodes (cf. Fig. 5) is commonly used for a variety of purposes.[1] Much experimental data and several discussions of the theory of the circuit have been published,[2] but the authors are not aware of the publication of any simple treatment, which enables one to calculate readily from the static tube characteristics alone the operating conditions, such as the current values and the frequency. In this paper a relatively simple method of determining these values is described. Only the symmetrical case, in which identical tubes and circuits are used, is treated, since this is the case of most interest.

ECCLES-JORDAN TRIGGER CIRCUIT

The operation of the multivibrator can best be understood from a discussion of the Eccles-Jordan trigger circuit,[3] in the simplified form shown in Fig. 1. Two identical triodes, to be subsequently referred to as I and II, with individual plate batteries E_b, and grid bias batteries E_{g1} and E_{g2} for I and II, respectively, are used. The two plate load resistances R_1 and R_2 are each equal to R. The currents in the several branches are indicated in the figure. The grid potentials for the two tubes are designated by e_{g1} and e_{g2}, respectively. In this circuit the currents i_{c1} and i_{c2} are equal to the grid currents i_{g1} and i_{g2} of I and II, respectively.

It has been found convenient to express potential differences in volts divided by R, that is, in current units. The ordinary grid-plate transfer characteristics of I, identical with those of II, are then expressed by

$$i_1 = f(E_b/\mu R + e_{g1}/R),$$

or, since E_b is constant, we may write

$$i_1 = \phi(e_{g1}/R),$$

where the function ϕ depends upon the parameter E_b. This characteristic is shown by curve (a), Fig. 2, in which both ordinates and abscissas are expressed in amperes. The discussion is further simplified by the use of the dynamic characteristic, computed for the plate load R, which is

$$i_1 = f(E_b/\mu R - Ri_1/\mu R + e_{g1}/R) = \phi(e_{g1}/R - i_1/\mu) = \psi(e_{g1}/R).$$

The ψ curve (b), Fig. 2, is derived from the ϕ curve by shifting each point on the latter hori-

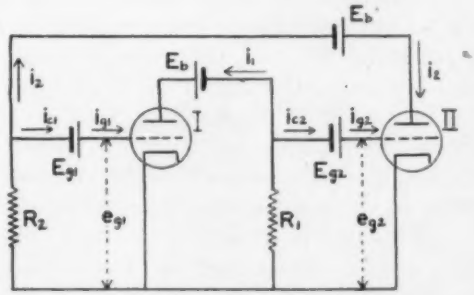

FIG. 1. Eccles-Jordan trigger circuit.

* Publication assisted by the Ernest Kempton Adams Fund for Physical Research of Columbia University.

[1] H. Abraham and E. Bloch, Ann. de physique **12**, 237 (1919).

[2] B. van der Pol, Phil. Mag. **2**, 978 (1926). Y. Namba and S. Namba, Elec. Lab. Tokyo Research **218** (1927). Y. Watanabe, Proc. I. R. E. **18**, 327 (1930). J. Mercier, L'Onde Electrique **13**, 197 (1934). S. C. Snowden, Phys. Rev. **65**, 151 (1944).

[3] W. H. Eccles and F. W. Jordan, Radio Rev. **1**, 143 (1919).

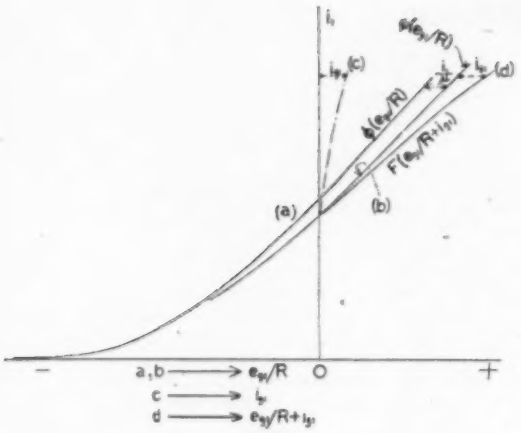

FIG. 2. (*a*) Grid-plate transfer characteristic. (*b*) Transfer characteristic with plate load R. (*c*) Grid current-plate current characteristic. (*d*) Transfer characteristic with plate load R and series resistance R in grid circuit.

zontally to the right by i_1/μ. The grid current in I, i_{g1}, is plotted on the abscissa axis, curve (*c*), so as to be a function of i_1, the scale being the same as that used for the other curves. It must be noted that i_{g1} depends upon the plate voltage, so that a new i_{g1} *vs.* i_1 curve must be constructed, if either E_b or the plate load is changed. In the circuit of Fig. 1, $e_{g1}=E_{g1}-R(i_2+i_{c1})$ and $e_{g2}=E_{g2}-R(i_1+i_{c2})$. Hence the following equations give the tube currents:

$$i_1=\psi(E_{g1}/R-i_2-i_{c1}), \qquad (1)$$

$$i_2=\psi(E_{g2}/R-i_1-i_{c2}). \qquad (2)$$

The more exact expression for (1) includes a term $-i_{c2}/\mu$ in the argument, since the current in R_1 now has the value i_1+i_{c2}, instead of i_1, for which the ψ curve was drawn. However, since μ is generally large and i_{c2} small, this term is usually negligible. Similarly in (2) a term $-i_{c1}/\mu$ has been omitted.

We will further simplify the calculations by the introduction of a third transfer characteristic, which takes into account the contribution to the grid potential of I of the voltage drop in R_2 caused by the grid current $i_{g1}=i_{c1}$. This curve (*d*), Fig. 2, is $F(e_{g1}/R+i_{g1})$, for which the abscissas are $e_{g1}/R+i_{g1}$, and is derived from curve (*b*) by shifting each point thereon horizontally to the right by the corresponding value of i_{g1}. This curve could have been obtained directly as the relation between the plate current and the grid bias battery voltage in a simple tube circuit with load resistance R and a resistance R in series with the grid. Using this characteristic, we have in place of (1) and (2),

$$i_1=F(e_{g1}/R+i_{g1})=F(E_{g1}/R-i_2)=F(p_1-i_2), \quad (3)$$

$$i_2=F(e_{g2}/R+i_{g2})=F(E_{g2}/R-i_1)=F(p_2-i_1), \quad (4)$$

where $p_1=E_{g1}/R$ and $p_2=E_{g2}/R$.

The values of i_1 and i_2, for which the system of Fig. 1 will be in equilibrium, are obtained by solving (3) and (4) as simultaneous equations. In Fig. 3 these equations have been plotted for fixed values of p_1 and p_2, the variables being i_1 and i_2. Curve J gives i_1 as a function of i_2 [Eq. (3)], while K gives values of i_2 with i_1 as the independent variable [Eq. (4)]. It should be noted that J is asymptotic to the horizontal axis and continues indefinitely along it, since i_1 is determined for all values of i_2. Similarly K must be continued indefinitely along the vertical axis. Each intersection of J and K corresponds to a solution of the simultaneous equations and therefore gives a pair of values of i_1 and i_2 for which the system is in equilibrium. Figure 3(*a*) represents a case in which R is less than a certain critical value, and the curves have only one intersection, which represents a condition of stable equilibrium. In Fig. 3(*b*), J and K curves are shown for a value of R greater than the critical value, the four J curves, J_1, J_2, J_3, and J_4 being drawn for increasing values of p_1, i.e., of E_{g1}. The J and K curves may now have three intersections, such as s_3', u, and s_3 between J_3 and K, giving three possible solutions. Or there may be one as in the case of J_1 and K, or one intersection and a point of tangency t_2, as in the case of J_2 and K. (See also t_4 for J_4 and K.)

The intersection at u represents a condition of unstable equilibrium, since the absolute value of the slope di_1/di_2 of K is less at this point than that of J_3. On the other hand, s_3' and s_3 are points corresponding to stable equilibrium, since at these intersections the absolute values of the slope of K are greater than those of J_3. This criterion for determining whether an intersection of these curves corresponds to unstable or stable equilibrium can be got directly from a consideration of the meaning of the J and K curves, or it may be formally derived as follows: In order that there may be determinate values for i_1 and i_2 for other than the equilibrium values, as during the passage from one condition to another, there must be reactance somewhere in the circuit. We will assume all reactances to be zero except a very small inductance L in the circuit between

I and E_b. Equations (3) and (4) then become

$$i_1 = F\left(p_1 - i_2 - \frac{L}{\mu R} di_1/dt\right), \tag{5}$$

$$i_2 = F(p_2 - i_1), \tag{6}$$

which equations must be satisfied whether the system is in equilibrium or not. In the following we need consider only the behavior of i_1, since by (6) i_2 is uniquely determined by i_1. Differentiating (5) and (6) with respect to the time, we have

$$di_1/dt = F'\left(p_1 - i_2 - \frac{L}{\mu R} di_1/dt\right) \times \left(-di_2/dt - \frac{L}{\mu R}\frac{d^2 i_1}{dt^2}\right), \tag{7}$$

$$di_2/dt = F'(p_2 - i_1)(-di_1/dt), \tag{8}$$

where F' is the derivative of F with respect to its argument. Substituting the value of di_2/dt from (8) in (7), we find

$$d^2 i_1/dt^2 = -\frac{\mu R}{L}\frac{di_1}{dt} \times \left[\frac{1}{F'\left(p_1 - i_2 - \frac{L}{\mu R}\frac{di_1}{dt}\right)} - F'(p_2 - i_1)\right] = -\eta \frac{di_1}{dt}. \tag{9}$$

When the system is very close to equilibrium $(L/\mu R)di_1/dt$ is vanishingly small, $-F'[p_1 - i_2 - (L/\mu R)di_1/dt]$ is the slope of J at the equilibrium point, and $-F'(p_2 - i_1)$ is the reciprocal of the slope of K at the same point. Hence η, which is proportional to the difference between the reciprocals of the slopes of the two curves at the equilibrium point, can be taken as constant. The solution of (9) is then,

$$di_1/dt = Ae^{-\eta t}. \tag{10}$$

Now let the system, initially at equilibrium, be slightly disturbed, say by a sudden small change in p_1. There will then be a finite initial value of di_1/dt equal to A, and from (10) we see that the absolute value of di_1/dt will increase indefinitely with the time and the system will depart more and more from the equilibrium condition, or the absolute value of di_1/dt will decrease with the time and the system will again return to equilibrium corresponding to the new value of p_1, according to whether η is negative or positive. Hence the equilibrium is unstable or stable as the absolute value of the slope of K is less or greater than that of J. (Note that both are intrinsically negative.) This criterion may be written

$$F'(p_1 - i_2)F'(p_2 - i_1) \gtrless 1, \tag{11}$$

the upper and lower signs of inequality corresponding to unstable and stable equilibria, respectively. This is essentially the same as the criterion given by other authors.

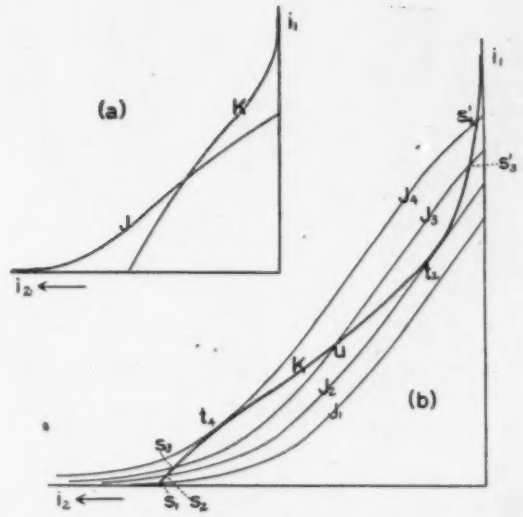

FIG. 3. Curves showing equilibrium conditions for trigger circuit. Curves are the same as (*d*), Fig. 2.

BEHAVIOR OF CIRCUIT WITH VARIATION OF GRID BIAS

Let E_{g1} be varied while E_{g2} is held constant. From Eq. (3) it is seen that an increase (decrease) in E_{g1} simply causes a shift in the J curve to the left (right) by the corresponding change in the value of p_1, since only the difference between p_1 and i_2 appears in the argument. Let the system be initially in the condition described by the s_3' intersection of the J_3 and K curves. Here I is the "active" tube and II the "inactive" tube. As E_{g1} is decreased J moves to the right and the points of intersection s_3' and u gradually approach one another, coinciding at t_2 when J reaches the position J_2, and the two curves are tangent. A further small decrease in E_{g1} leaves only the intersection at s_2, and therefore the

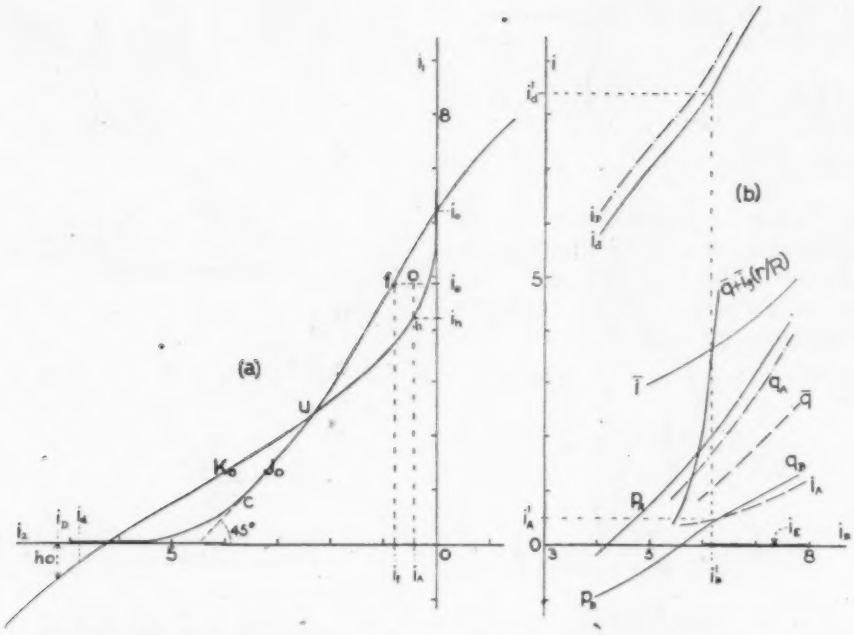

FIG. 4. (*a*) Diagram for determining trigger characteristics. Circuit with 6N7 tubes ($\mu=35$), $R=1000$ ohms, $r=20000$ ohms, $E=150$ volts. Coordinates in milliamperes. The ordinate of K_0 at $i_2=i_d$ is $-[ho-(i_B-i_{gd})R/r]$. (*b*) Trigger characteristics. Coordinates in milliamperes. $p_A=ho$; $p_B=fo$. q_A lies $(R/r)i_h$ below p_A. q_B lies $(R/r)i_f$ below p_B; when $i_B>i_0$, i_f is negative and q_B lies above p_B. In the diagram p_B and q_B are drawn coincident, since their difference was small. i_E is practically zero.

system passes abruptly from the condition represented by the point t_2 to that represented by s_2, with I now the inactive tube and II the active one. This abrupt change in the condition of the system is referred to as "triggering." Further decrease in E_{g1} shifts J further to the right, say to J_1, with s_1 describing the equilibrium. Now let E_{g1} be steadily increased. J will now shift to the left passing through the positions J_2 and J_3, until J_4 is reached with t_4 the equilibrium point, and any further increase in E_{g1} will cause triggering from II to I with the system passing abruptly from t_4 to s_4'.

TRIGGER CHARACTERISTICS

The behavior of the trigger circuit is conveniently described by a set of curves, the "trigger characteristics," which give the values of the currents in the tubes just before and just after triggering and the corresponding values of p_1 and p_2. Figure 4(*b*) shows such a set of curves for a circuit using two 6N7 triodes, with $E_b=150$ volts and $R=1000$ ohms, and gives values for triggering from a state in which I is the active tube to one in which II is the active tube. Here i_B = the current in I before triggering, i_A = the current in II before triggering, i_E = the current in I after triggering, i_D = the current in II after triggering, p_A = the value of p_2 when triggering occurs, and p_B = the value of p_1 when triggering occurs. The independent variable is i_B, plotted on the axis of abscissas. The points through which these curves were drawn were determined from Fig. 4(*a*), an i_1 *vs.* i_2 plot similar to those in Fig. 3(*b*), J_0 and K_0 being drawn for $p_1=p_2=0$, i.e., for $E_{g1}=E_{g2}=0$. Now it has been shown that triggering occurs when the curves J and K are tangent. Hence if triggering is to take place for a given value of i_B, J must be shifted from the J_0 position horizontally by the amount p_B and K from the K_0 position vertically by the amount p_A, so that the two curves will touch at points of equal slope. In Fig. 4(*a*), J_0 has at the point f, which corresponds to $i_1=i_B$, the same slope as K_0 has at the point h. J and K must therefore be shifted from their initial positions until they are tangent at o, which gives $p_B=fo$ and $p_A=ho$. (Note that in the figure fo is negative and ho positive.) To facilitate the construction the curves are continued beyond the axes, but these continuations have no physical meaning, since neither i_1 nor i_2 can have negative values. The current in the inactive tube before

triggering, i_A, is equal to the abscissa of h. The values of the currents in the tubes after triggering, i_E and i_D, are given by the ordinate and abscissa, respectively, of the left-hand intersection of the shifted J and K curves. In most cases of interest i_E is practically zero and i_D is determined by the intersection of the shifted K curve and the i_2 axis, or more simply, is equal to the abscissa of the point on K which lies below the i_2 axis by the amount $p_A(ho)$, as indicated in the figure. By repeating this construction for several values of i_B, the curves in Fig. 4(b) were obtained, giving the values of i_D, i_A, and i_E (in this case i_E is practically coincident with the i_B axis), as well as p_A and p_B, as functions of i_B. These curves are usually nearly linear in the range of interest and can therefore be determined from a few points.

MULTIVIBRATOR

The circuit of the symmetrical multivibrator is shown in Fig. 5. The battery E_{g1} of Fig. 1 has been replaced by the condenser C_1 with the grid leak resistance r_1, and E_{g2} by C_2 with leak resistance r_2. The condensers are of equal capacities C, and $r_1=r_2=r$. Usually r is ten to twenty times greater than R. The instantaneous charges on the condensers C_1 and C_2 are Q_1 and Q_2, respectively. The grid bias potential E_{g1} of the Eccles-Jordan circuit has now to be replaced by $Q_1/C-Ri_{r1}$, the second term appearing since we have

$$i_{c1}=i_{g1}+i_{r1}. \tag{12}$$

Hence $p_1=Q_1/RC-i_{r1}=q_1-i_{r1}$. Similarly E_{g2} is replaced by $Q_2/C-Ri_{r2}$, and $p_2=Q_2/RC-i_{r2}=q_2-i_{r2}$. Equations (3) and (4) then become,

$$i_1=F(q_1-i_{r1}-i_2), \tag{13}$$

$$i_2=F(q_2-i_{r2}-i_1). \tag{14}$$

During the half-period when I is active, C_1 will discharge and C_2 will charge. When triggering occurs $p_2=p_A$ and $p_1=p_B$. The corresponding values of q_2 and q_1 are designated by q_A and q_B, respectively.

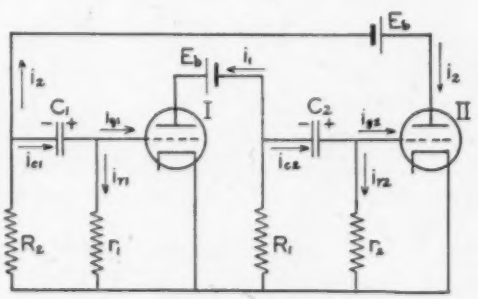

FIG. 5. Symmetrical multivibrator circuit.

The current in II after triggering, i_d, is slightly less than i_D, the corresponding current in the Eccles-Jordan circuit, since, when triggering occurs from I to II, i_{r2} changes by an amount closely equal to

$$(i_B-i_E-i_{gd})R/(R+r),$$

where i_{gd} is the grid current in the tube when the plate current is i_d. This can be shown by writing the circuit equations for the path $R_1C_2r_2$ before and after triggering. This expression can be simplified to $(i_B-i_{gd})R/r$, since i_E is very nearly zero and r is much greater than R. This abrupt change in i_{r2} causes a downward shift of K equal to this amount. We can therefore determine i_d by following the procedure described for determining i_D, using $p_A-(i_B-i_{gd})R/r$ instead of p_A. The difference between i_d and i_D is usually small, since R/r is small.

To find the values of q_A and q_B from p_A and p_B we have, first, $q_A=p_A+i'_{r2}$, where i'_{r2} is the current in r_2 just before triggering. If e'_{g2} is the grid potential of II prior to triggering, we have $i'_{r2}=e'_{g2}/r$. From Fig. 4(a) we see that for $p_2=0$, a current $i_1=i_h$ in I will reduce i_2 to i_A. Hence $e'_{g2}=-Ri_h$, $i'_{r2}=-Ri_h/r$, and the q_A curve lies $(R/r)i_h$ below the p_A curve. Similarly $q_B=p_B+i'_{r1}$, where i'_{r1} is the current in r_1 just before triggering. If the grid current in I is negligible at this instant, $e'_{g1}=-Ri_f$ and $i'_{r1}=-i_fR/r$. It should be noted that i'_{r1} is positive for values of i_B greater than i_0, where i_0 is the value of i_1 on the J_0 curve for $i_2=0$. The curve for q_B will lie above or below the p_B curve according to whether i_B is greater or less than this value. (Since the J and K curves include the effects of the voltage drops caused by the grid currents in the resistances R_2 and R_1, respectively, it is necessary to substitute $i_f+i'_{g1}$ for i_f in the expression for i'_{r1}, if i'_{g1}, the grid current in I just before triggering, is not negligible.) In many cases i'_{r1} is small, and the q_B and p_B curves are nearly coincident, as in the case shown in Fig. 4(b).

To find i_B', the operating value of i_B for any given multivibrator circuit, we use the circuit equation for the circuit $R_2C_1r_1$,

$$Ri_2+Ri_{c1}-Rq_1+ri_{r1}=0. \tag{15}$$

Multiplying this equation by dt and integrating over one complete period T and dividing by RT, we find,

$$\frac{1}{T}\int_0^T i_2dt+\frac{1}{T}\int_0^T i_{c1}dt - \frac{1}{T}\int_0^T q_1dt+\frac{r}{RT}\int_0^T i_{r1}dt=0. \tag{16}$$

The second integral equals zero. From (12) we see that the last integral equals

$$-\frac{r}{RT}\int_0^T i_{g1}dt.$$

We have therefore,

$$\bar{i}_2=(r/R)\bar{i}_{g1}+\bar{q}_1, \tag{17}$$

where the bars indicate mean values for a complete period. For this part of our calculation a good approximation is

$$\bar{i}_2=\bar{i}_1=\tfrac{1}{4}(i_B+i_d+i_E+i_A)=\bar{i}. \tag{18}$$

In Fig. 4(b) $\bar{i}$ is plotted as a function of i_B. The mean value $\bar{q}_1$ can be taken as approximately equal to the mean of q_A and q_B, or in many cases the mean of p_A and p_B is sufficiently close. The approximate value of the mean grid current $\bar{i}_{g1}$ can be calculated by assuming that the plate current changes linearly with the time from i_d to i_B, and that the instantaneous grid current is proportional to i_d-i_0, which gives

$$\bar{i}_{g1}=\bar{i}_{g2}=\bar{i}_g=\tfrac{1}{4}i_{gd}(i_d-i_0)/(i_d-i_B), \tag{19}$$

i_{gd} being the grid current when the plate current is i_d. In Fig. 4(b) the sum $\bar{q}+(r/R)\bar{i}_g$ is plotted as a function of i_B. The intersection of this curve with the $\bar{i}$ curve determines i_B', the value of i_B for which (17) is satisfied. In the following discussion the operating values of the other variables, as determined from Fig. 4, will similarly be designated by primes, *viz.*, i_d', q_A', i_b', etc.

The rapid rise in the value of $(r/R)\bar{i}_g$ with increase in i_B makes it possible to use the above approximations and still arrive at a reasonably precise value of i_B'. It will be noted that the grid current plays a very important part in the behavior of the multivibrator, since on it depend the operating values of the currents and to a great extent the period of oscillation. If the grid current were not involved, i_B' would be very large, since it would then be fixed by the intersection of the $\bar{i}$ curve and the $\bar{q}$ curve, which have nearly the same slopes.

PERIOD

During the half-period in which tube I is inactive, the charge on condenser C_1 increases from RCq_B' to RCq_A'. During this time no grid current flows in I, and we have,

$$i_{c1}=i_{r1}=-RCdq_1/dt. \tag{20}$$

Equation (15) may then be written

$$\frac{dq_1}{dt}+\beta q_1-\beta i_2=0, \tag{21}$$

where $\beta=1/(R+r)C$. Multiplying by $e^{\beta t}$ and integrating with respect to the time from 0 to $T/2$, we get

$$e^{\beta T/2}q_A'-q_B'-\beta\int_0^{T/2} e^{\beta t}i_2dt=0. \tag{22}$$

The exact evaluation of the integral in the third term is not possible, since we do not know the exact form of the relation between i_2 and t. If we set this term equal to $-i_M(e^{\beta T/2}-1)$, (22) gives

$$e^{\beta T/2}=\frac{i_M-q_B'}{i_M-q_A'}, \tag{23}$$

from which we have

$$T=2C(R+r)\ln\frac{i_M-q_B'}{i_M-q_A'}. \tag{24}$$

The simplest approximation for i_M is

$$i_M=\tfrac{1}{2}(i_d'+i_B'), \tag{25}$$

which is usually sufficiently precise for computing the period. If the ratio of i_d' to i_B' is less than 1.4, a good approximation for i_2 is, $i_2=i_d'e^{-\alpha t}$, where $\alpha=(2/T)\ln(i_d'/i_B')$, and it can be shown that the percentage error in i_M, as determined by (25), is then equal to

$$-\frac{100}{12}\left[\left(\frac{\alpha T}{2}\right)^2+\alpha\beta\left(\frac{T}{2}\right)^2\right]. \tag{26}$$

Since in all cases in which the method can be used with fair precision both $\alpha T/2$ and $\beta T/2$ are less than 1.3, the use of (25) results in an error in the value of i_M of less than two percent, with approximately the same error in the period, which is less than the error attributable to inaccuracies in the graphical operations. For large values of R the ratio i_a'/i_B' is greater and this error in i_M increases, becoming as large as ten percent in actual circuits studied. However, in these cases a much greater error results from the neglect of the actual form of the i_2-time curve. Because of the large grid current in the active tube immediately after triggering, this curve dips sharply initially, so that the correct value of the integral in (22) is much smaller than is given if we use (25) and the correction (26). Since other errors caused by approximations in computing the grid current and determining the operating value of i_B are also large in these extreme cases, little is gained by using more accurate methods of computing i_M. The formulas (24) and (25) are the best working formulas which the authors have been able to devise without resorting to trial and error methods too laborious to be useful.

It should be noted that in most cases in which the method gives satisfactory results q_B' is small compared to i_M, and the argument of the logarithm term in (24) can be written with good approximation,

$$\left(1-\frac{q_A'-q_B'}{i_M}\right)^{-1}=(1-\gamma)^{-1}.$$

If, as is usually the case, γ is small (less than 0.25), $\ln(1-\gamma)^{-1}$ is approximately equal to γ, the difference being less than ten percent in most cases. Hence the frequency depends almost directly upon the values of i_M and the difference between the maximum and minimum charges on the condensers.

EXPERIMENTAL TESTS

A series of tests was made to determine how closely one can predict the behavior of a given multivibrator by the methods described above, starting with the ordinary tube characteristics. The circuit contained two 6N7 triodes, selected to have nearly identical characteristics. In order to observe the tube currents on an oscillograph a resistance of 1000 ohms was inserted in each plate circuit next to the tube. The tube characteristics from which the calculations were made were corrected to include the effect of this resistance, so that the computations were not affected. The behavior of the Eccles-Jordan circuit was first tested and the results agreed well with those predicted from the trigger characteristics.

In the tests of the multivibrator circuit a single-plate battery was used in the usual way instead of the two shown in the figure. This alters conditions by adding a fixed negative charge $-CE_b$ to each condenser, decreasing both p_A and p_B by E_b/R. The values of p_A and p_B are unchanged, however, since they now include the plate battery voltage, which adds to each the term E_b/R. Hence our equations are unaffected. Equation (24) shows that the period should vary directly as the capacity of the condensers C. With $R=1000$, $r=20000$ ohm, and $E_b=150$ volts the relation between the period and capacity was a straight line for values of C between 1 μf and 0.05 μf (frequency $=1870$), but for smaller values of C the period increased more rapidly, being 14 percent higher than the value given by the straight line relation for $C=0.003$ μf (frequency $=29{,}400$). With $R=2000$ ohms and the other parameters as above the linear relation held well to $C=0.005$ μf (frequency $=7200$). When R was reduced to 700 ohms the linear relation was followed closely only to $C=0.1$ μf (frequency $=3050$); the period was 60 percent too high for $C=0.008$ μf (frequency $=25{,}600$). Since the above treatment does not take into account the effect of the distributed reactances, which cause these deviations, all the experimental tests to be described were made in the frequency ranges for which the period was proportional to C.

The frequencies were measured with a calibrated beat frequency oscillator in conjunction with a cathode-ray oscillograph. The currents were measured with the oscillograph, using known alternating voltages for calibrating the scale. Several values of R and E_b were used covering the range of satisfactory operation of the multivibrator, and two values of r, 20,000 and 50,000 ohms, respectively. The results of these tests are tabulated in Table I. The experimentally determined values are in roman type and beneath each in italics are the corresponding values calculated from the static tube characteristics, using the procedures described above. The experimental values of $q_A'-q_B'$, given in the seventh column, were obtained from the variation of voltage across one of the condensers, as measured on the oscillograph and divided by R.

TABLE I. Experimental values are in roman type; calculated values are directly beneath in italics.

R	r	E_b	C	i_B'	i_d'	$q_A'-q_B'$	Frequency
ohms		volts	μf	milliamperes			
1000	20000	196	0.1	8.4	11.9	2.50	765
				8.6	*12.1*	*2.55*	*820*
	50000	196	0.1	—	—	—	322
							320
1000	20000	150	1.0	6.0	8.1	1.36	97
				6.2	*8.5*	*1.40*	*94*
	50000	150	1.0	5.6	7.7	1.20	42
				5.6	*8.1*	*1.27*	*47*
1000	20000	92	0.1	3.5	4.2	0.48	1680
				3.1	*4.4*	*0.49*	*1520*
900	20000	150	1.0	5.8	8.1	1.10	120
				6.0	*7.8*	*1.05*	*134*
	50000	150	0.1	4.8	7.3	1.02	545
				5.5	*7.6*	*0.92*	*615*
800	20000	150	1.0	5.6	7.7	0.75	184
				5.9	*7.6*	*0.73*	*190*
	50000	150	0.1	5.1	7.1	0.68	850
				5.4	*7.2*	*0.67*	*858*
2000	20000	196	0.1	8.2	16.5	4.6	345
				7.8	*16.4*	*4.4*	*500*
	20000	150	1.0	5.7	12.0	3.1	37
				5.4	*10.6*	*2.8*	*52*
	50000	150	0.1	5.1	10.7	2.9	147
				4.3	*9.0*	*2.7*	*268*
	20000	92	0.1	3.2	5.8	1.50	440
				3.2	*5.5*	*1.45*	*550*
700	20000	196	0.1	7.8	10.7	0.90	2040
				8.9	*10.5*	*1.00*	*2050*
	20000	150	1.0	5.1	7.3	0.41	335
				6.1	*7.6*	*0.45*	*317*
	50000	150	0.1	4.6	6.1	0.39	1650
				5.3	*6.6*	*0.20*	*2740*

The values of i_A' are not listed since they were not measured with sufficient precision. The measured values of i_E' were zero in every case.

With the exception of the measurements made with $R=2000$ and $R=700$ ohms, the agreement between experimental and computed values is satisfactory. The calculated frequencies agree with the measured values on the average within six percent. The experimental and calculated values of the currents, i_B' and i_d', differ in only a few cases by more than the experimental error. The greatest source of error was in the determination of i_B', because of the approximate method used in calculating the mean grid current, which often gave values differing considerably from those actually measured on a direct current meter in the grid circuit. This error was especially serious for $r=50{,}000$ ohms, since the ratio r/R, by which the mean grid current is multiplied when determining the operating point, was large. Errors in i_d' were in many cases large because of the lack of precision in finding the absolute value of p_A, which depends upon the location of a point of given slope on the lower part of the tube characteristic. Unless great care is taken in drawing this part of the curve errors as large as 0.2 milliampere may result. On the other hand, errors made in determining q_A' and q_B' cancel one another to a considerable extent and the difference $q_A'-q_B'$ is found with higher precision than that of either term. In the measurements made with R equal to 1000, 900, and 800 ohms, respectively, the experimental and computed values of $q_A'-q_B'$ differed on the average by only two percent. As already pointed out, it is this difference between the charges that is important in determining the frequency rather than their absolute values.

With $R=2000$ ohms much larger differences were found between the predicted and observed values of the currents and frequencies. Oscillograms showed that the plate current *vs.* time curve in the active half-period dropped sharply initially and departed considerably from the exponential curve assumed in our approximation for i_M. This resulted in two errors. First, the estimated mean grid current was too large, resulting in calculated values of i_B' and i_d' which were too low. Second, in spite of the low calculated values of these currents the value of i_M given by (25) was much too high, giving high values of the calculated frequency. In the case of the measurements made with $R=2000$ ohms, $r=20000$ ohms, and $E_b=150$ volts, the integration in the last term of (22) was carried out graphically, using the measured period and the data from an oscillograph trace of i_2. The value of i_M found was thirty percent smaller than the value given by (25), which gave the calculated frequency 52. Using the lower correct value of i_M the computed frequency was 34, agreeing reasonably well with the observed value, 37. It should be noted that even in these cases the calculated values of $q_A'-q_B'$ agree well with the observed.

The calculated values for $R=700$ ohms also show poor agreement with the measured. Here the value of R is very near the lower limit for which the circuit will oscillate, and the J_0 and K_0 curves have very nearly the same slopes, making accurate graphical construction very difficult. Furthermore, with this value of R the triggering was no longer sharp, indicating that distributed capacities were no longer negligible. Hence only rough agreement was to be expected. The discrepancies are particularly large in the

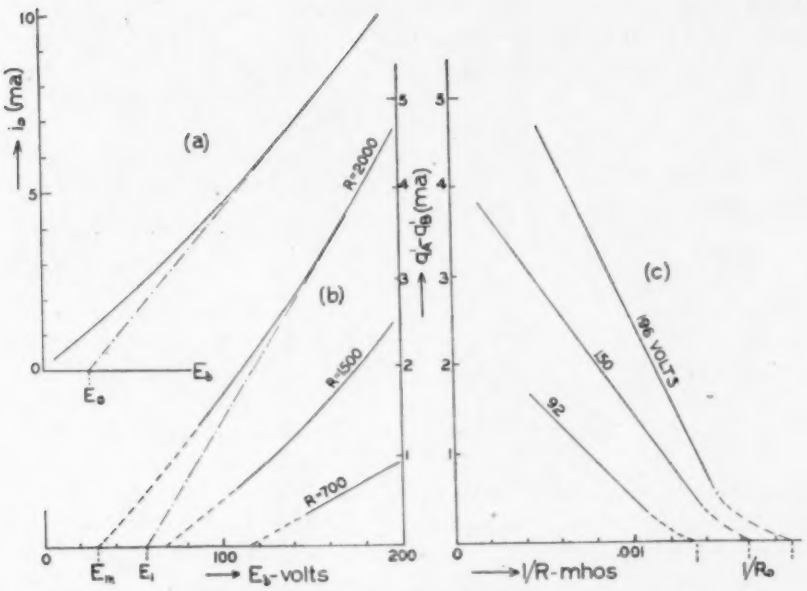

FIG. 6. Performance of multivibrator circuit with variation of parameters. (*a*) i_b *vs.* E_b. E_0 is the intersection on the E_b axis of the tangent to the curve at $E_b=150$. (*b*) $q_A'-q_B'$ *vs.* E_b. E_1 is the intersection on the E_b axis of the tangent at $E_b=150$. E_m is the calculated minimum voltage for vibration. (*c*) $q_A'-q_B'$ *vs.* $1/R$. R_0 is the calculated minimum value of R for vibration.

i_B' column and in the measurements with $r=50{,}000$ ohms.

In the actual construction of the trigger characteristics advantage can be taken of the symmetry in Fig. 4(*a*), which permits the determination of i_d from the upper part of the J_0 curve, which is the same as the lower part of K_0. Consequently, only those parts of the J_0 and K_0 curves which lie near the i_1 axis need be constructed. If less precision is permissible, other simplifications may be made in the calculations by neglecting some or all of the effects of the currents in r_1 and r_2.

GRID BIAS

To simplify the preceding discussion the effects of fixed grid biases were omitted. It can be readily shown, however, that the introduction of a fixed negative bias voltage V into each grid circuit between the tube and the branch point affects only the charges on the condensers, and that in Fig. 4(*b*) all the ordinates of the curves for q_A, q_B, and q are increased by V/R. This results in decreases in the values of i_B', i_d', i_M, and $q_A'-q_B'$. The same values of the currents and period are obtained if the bias voltage is shifted to the r_1 and r_2 branches, although the charges on the condensers are then the same as without bias. The use of a cathode bias resistor, of resistance r_K, results only in changing the shape of the ψ and F characteristics shown in Fig. 2, and therefore of the derived curves J_0 and K_0 in Fig. 4(*a*). The difference between the ϕ and ψ curves becomes $i_1/\mu+(r_K/R)(i_1+i_{g1})$ instead of i_1/μ.

VARIATION OF THE PARAMETERS

The effect on the period of varying C has been discussed earlier. It is of interest to examine the effects of changing the other parameters r, R, and E_b. Since r is usually very large compared with R, the factor $R+r$ in the expression for the period varies nearly linearly with r, while the value of the logarithm term changes only slowly with r. We find then that the period should be approximately proportionate to r, as is observed experimentally. On the other hand, a change in R affects the period chiefly through the logarithm term. The period is affected by changes in E_b only through the logarithm term. As pointed out above, this term varies approximately as γ, the ratio of $q_A'-q_B'$ to i_M.

In Fig. 6(*b*) the values of $q_A'-q_B'$, taken from Table I, are plotted as a function of E_b, for three values of R. Figure 6(*c*) shows the variation of $q_A'-q_B'$ with $1/R$ for three values of E_b. In Fig. 6(*a*) i_0 is plotted as a function of E_b for $R=2000$ ohms.

To find the effect on the period of changing only E_b, we differentiate γ with respect to E_b and divide by γ. If we use the approximation $i_M = i_0 \times$constant,

$$\frac{1}{\gamma}\frac{\partial\gamma}{\partial E_B} = \frac{1}{q_A' - q_B'}\frac{\partial(q_A' - q_B')}{\partial E_b} - \frac{1}{i_M}\frac{\partial i_M}{\partial E_b}$$

$$= \frac{1}{E_b - E_1} - \frac{1}{E_b - E_0} \qquad (27)$$

$$= \frac{E_1 - E_0}{(E_b - E_1)(E_b - E_0)},$$

where E_1 and E_0 are the respective intercepts on the E_b axis of the tangents to the $q_A' - q_B'$ and i_0 curves at points corresponding to the value of E_b in question. The fractional change in γ, corresponding to a given change in E_b, therefore decreases rapidly with increase in E_b. It depends also directly upon the difference between E_1 and E_0, which, as may be seen from the figure, changes little with E_b, but falls off rapidly with increase in R.

If E_b and r are held constant and R alone varied, i_M remains nearly constant but $q_A' - q_B'$ is approximately a linear function of $1/R$, as shown in Fig. 6(*c*). If we neglect the changes in the characteristics resulting from the changes in the plate load and other lesser effects of the changes in R, we find that as R is varied the curves in Fig. 4(*a*) are altered by varying the abscissas of J_0 and the ordinates of K_0 so that they remain proportional to $1/R$, while the ordinates of J_0 and the abscissas of K_0 remain constant. If we further neglect small changes caused by variation in the value of i_A', and note that K_0 intersects the i_2 axis at $i_2 = i_0$, we find the approximate relation,

$$i_k' = i_0 \tan\theta + \text{const.}, \qquad (28)$$

where θ is the angle between K_0 and the i_2 axis. But $\tan\theta = 1/g_m' R$, g_m' being the mutual conductance with plate load resistance R. From (28) we have,

$$di_k'/d(1/R) = i_0/g_m'. \qquad (29)$$

Now $\gamma i_M = q_A' - q_B' = i_B' - i_k'(r+R)/r - i_A' + i_f'(r+R)/r$. Since $i_B' - i_A' + i_f'(r+R)/r$ and i_M change only slowly with R, we find the approximate relation,

$$\partial\gamma/\partial(1/R) = -\frac{1}{i_M}\frac{\partial i_k'}{\partial(1/R)} = -i_0/(i_M g_m'). \qquad (30)$$

The slopes of the curves in the figure agree well with the values computed by (30) when multiplied by i_M.

LIMITING VALUES

The minimum voltage E_m for which the circuit will vibrate for a given value of R can be calculated approximately from the J_0 and K_0 curves constructed for this value of R and some known value of E_b, E_b'. A decrease in E_b of ΔE_b is equivalent to a decrease in the grid voltage of $\Delta E_b/\mu$, which would shift the J_0 curve to the right and the K_0 curve down, each by the amount $\Delta E_b/\mu R$. If we continue to decrease the plate voltage we eventually reach a condition in which both curves have the same slope, -1, at their middle intersection, which is the theoretical limit for triggering and therefore of vibration. In Fig. 4(*a*) the point on J_0 with slope equal to -1 is marked *c*. To reach this limiting condition J_0 must be shifted to the right by an amount w, equal to the difference between the abscissa of *c* and its ordinate. Hence $E_m = E_b' - w/\mu R$. The values of E_m, determined in this manner for the several values of R, are indicated in Fig. 6(*b*) by the intercepts on the E_b axis of the extrapolated curves.

In a similar manner we can find the value of R_0, the minimum value of R for which the circuit will vibrate with a given value of E_b. This is the value of R for which the slope of J_0 at $i_1 = i_2$ is equal to -1. But this slope is

$$di_1/di_2 = R di_1/d(Ri_2) = -Rg_m.$$

Hence $1/R_0 = g_{m0}$, where g_{m0} is the mutual conductance determined with load resistance R_0 and grid potential $-R_0 i_2 = -R_0 i_1$. Using this procedure the values found for R_0 were 530, 610, and 740 ohms for E_b equal to 196, 150, and 92 volts, respectively. The reciprocals of these values are shown in Fig. 6(*c*) as the terminations on the axis of abscissas of the corresponding extrapolated curves.

The asymmetrical multivibrator may be treated in a similar manner. However, in this case the problem is much more complicated, since a separate trigger characteristic is required for each tube to compute the operating values of the tube currents and the partial periods.

Some Peculiarities of Heating Steel by Induction

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I. THE PRINCIPAL ELECTRICAL AND MAGNETIC CHARACTERISTICS OF STEEL

WHEN the dimensions of the object heated by induction are considerably more than the depth of penetration of currents $|Z|$, then the power taken by the object from the electromagnetic field is proportional to the value $(\rho\mu)^{\frac{1}{2}}$, named the power delivery factor, while the thickness of the layer $|Z|$ in which is concentrated most of the heat generated is proportional to $(\rho/\mu)^{\frac{1}{2}}$, ρ the resistivity, and μ the permeability of the material.

For low carbon steel at 20°C ρ has the value $10.10^{-6}\Omega$ cm and increases monotonously with the temperature attaining $100.10^{-6}\Omega$ cm at 800–900°C. Consequently, within the temperature range 20–800°C the resistivity increases about tenfold.

Carbon increases the ohmic resistivity of steel only when in the state of a solid solution. When carbon is present in steel in form of iron carbides, its action on the resistivity is inconsiderable. Therefore, the resistance of plain carbon steel containing up to 1 percent C in the annealed state (lamellar or granular pearlite) is little different from that of pure iron.

Other alloying elements, too, increase the resistivity of steel, though at the same time they decrease its temperature dependence. In alloys with high values of the resistivity (at 20°C) it will increase little with temperature.

At the temperature above the magnetic transmutation point (800–900°C), all alloys of iron have the resistivity $(120–130).10^{-6}\Omega$ cm.

The values of the magnetic permeability are much more scattered than those of the resistivity. Moreover, the permeability depends widely upon the magnetic field strength.

In fields of medium strength the permeability of low carbon steels ranges from 100 to 10,000. Following the most reliable data the permeability varies very little with the frequency, up to 10^7 cycles per second.

As the temperature is rising the permeability is decreasing. The point above which $\mu=1$ is the so-called Curie temperature—θ. For soft iron $\theta=768$°C. Cementite loses its magnetic properties at 216°C.

In high carbon and alloyed steels the permeability depends strongly upon the preceding thermal treatment. In the austenite state all steels are non-magnetic. The permeability of cementite is considerably less than that of ferrite. Therefore μ may have different values—depending upon the percentage of the carbides and the residual austenite.

In Figs. 1 and 2 the value $(\rho\mu)^{\frac{1}{2}}$ and the depth of penetration $|Z|$ are plotted against the temperature. These plots show how sharply

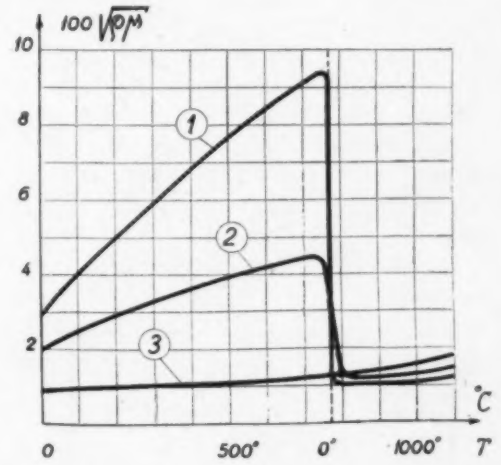

FIG. 1. (*1*). Carbon steel with 0.8–1.2 percent C. (*2*). Chrome steel. (*3*). Steel with 18 percent Cr and 8 percent Ni.

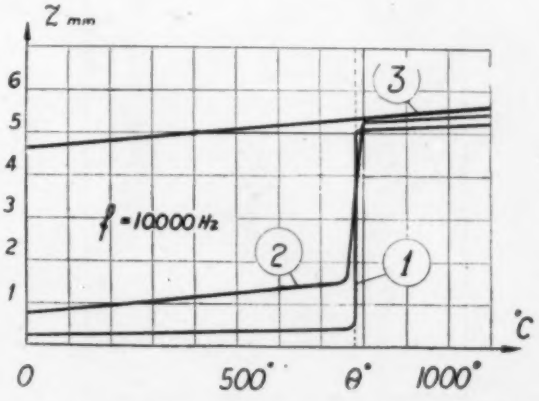

FIG. 2. Dependence of the depth of penetration from the temperature for the kinds of steel shown in Fig. 1 (the temperature uniform everywhere in the steel volume).

different is the power taken out of an electromagnetic field by different kinds of steel.

The higher $(\rho\mu)^{\frac{1}{2}}$, the shorter will be the heating time required to bring the object to the given temperature. For instance, heating to the $T=800$°C a ϕ 8-mm rod of steel with 0.8 percent C in a cylindrical coil with the current density 400A/cm requires 2 seconds. When treating in that same coil a rod of steel with 1 percent Cr, the temperature 800°C will be attained in the course of 4 seconds. The heating time for steel of the austenite type (e.g., Gadfield manganese steel or chrome-nickel stainless steel) will be 12 seconds.

The alloyed non-magnetic steels are "flabbily" heating themselves in the high frequency fields.

II. THE STRIATED HEATING EFFECT

Let us place a cylinder of magnetic steel in a heating coil (inductor) large enough so that the entire lateral surface of the cylinder is visible, and switch on the current. Heating will start. Suddenly on the cherry-red background there will flash bright orange strias. Their temperature may exceed 100–200°C that of the intervals. The general view of the cylinder will put in mind a tiger or zebra skin. Then the bright strias will expand, the dark intervals between them will become thinner, disintegrate to separate spots elongated in the direction of the eddy current lines, and finally disappear. Now the whole surface will be uniformly shining (temperature about 850°C).

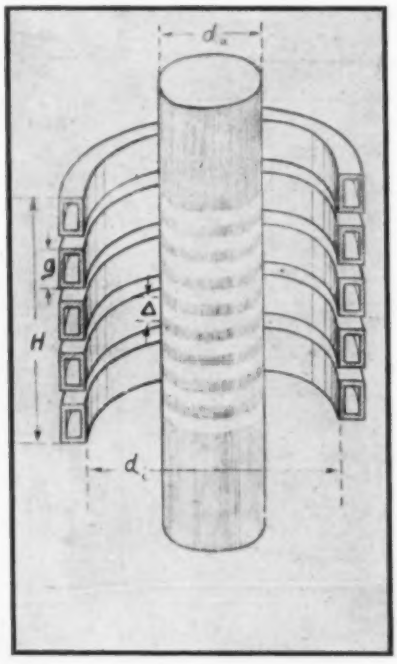

FIG. 3. Schematic view of a steel cylinder subjected to striated heating.

In Fig. 3 is shown schematically a steel object in the moment when strias have just appeared. This figure shows that the strias are directed along the lines of eddy currents. If, for instance, the steel cylinder were placed obliquely in the heating coil, the strias should be parallel with the turns of the coil.

Sometimes the strias are at first very thin and bright. Their width is ten- to twenty-fold less than that of the intervals. Then the bright strias begin to expand. The temperature in the middle of them falls. These middles extinguish while the rands of the strias washing out the dark intervals are shining still brighter.

The striated heating effect is observed only with materials having high values of permeability. It is the most pronounced in the case of soft iron (Armko iron), and further in carbon steel of the ferrite and pearlite types. Steels with low permeability show a much weaker effect. Moreover, the striated heating effect depends upon the preceding thermal treatment of steel (hardening, annealing).

When heating non-magnetic materials—e.g., austenite steel or graphite—the striated heating effect is not observed at all.

The described effect may be explained by the redistribution of current during the heating procedure. There may be distinguished the "forced striated heating" and the "natural striated heating."

A multiturn heating coil produces a non-uniform distribution of currents on the surface of steel. Places under the middles of the conductors are the first which attain the Curie temperature. The resistance of these places becomes much less than that of the surrounding metal. Currents from the neighboring places gather in these strips. The current density here sharply increases. The specific power in these places may exceed many times that in the surrounding metal. The surface of steel reflects the luminous pattern of the heating coil.

This is the case of "forced striated heating." The intervals between the strias are equal to the pitch of the heating coil. As soon as the whole surface of steel has passed in γ-solution, the original current distribution will re-establish. Hereby the strias will disappear and the non-

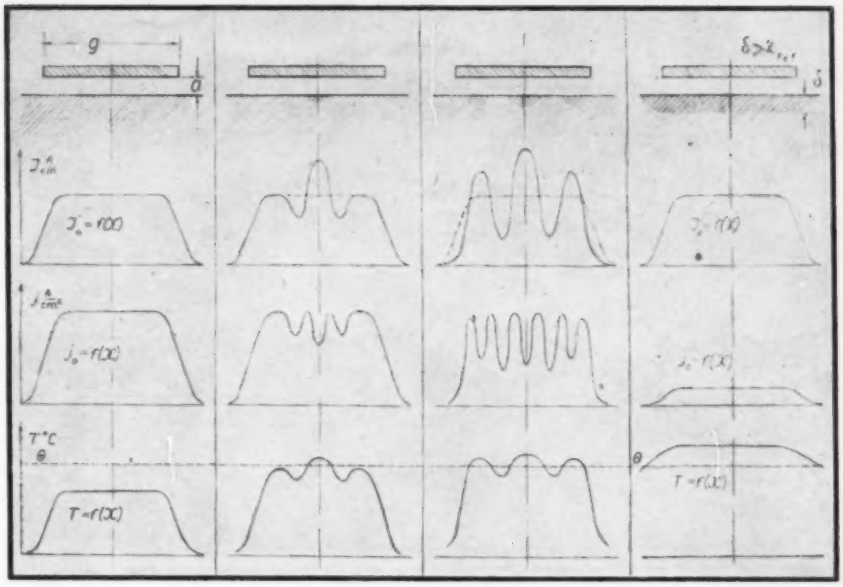

FIG. 4. Distribution of the current I, the current density j, and the temperature T over a steel surface. Vertical hatching indicates zones passed in γ-solution.

uniformity of temperatures will be of the same grade as the non-uniformity of the magnetic field produced by the inductor.

However, striated heating may occur, too, with a quite uniform field of the inductor. Let us consider an infinite steel plate with the current density uniform everywhere. Because of the inevitable non-uniformity of the material some spots on the surface will be the first to attain the Curie point. Lines of currents will be forced out thither from the surrounding metal. The zone with the diminished current density (from both sides of the heated strip) may have the width of the order of the depth of penetration of currents in heated steel at the given frequency. This zone will be heated more slowly. Next, luminous strips will arise on the rands of the dark zone. In this manner the surface of metal will become adorned with luminous and dark strias. This is the "natural striated heating." The interval between two neighboring strias is determined by $\Delta = \text{const.}/\sqrt{f}$. The magnitude of the constant depends both on the thermal and electrical properties of steel and on the specific power. It has been found that in most cases the interval between two adjacent strias is $2000/\sqrt{f}$; e.g., at the frequency 10^6 c.p.s. it is 2 mm and at the frequency 10^4 c.p.s.—20 mm. The intensity of the effect may be the same in both the single-turn and the multiturn heating coils. The number of strias may differ from that of the turns of the heating coil.

Striated heating may occur only on the condition that the specific power on the surface of steel is high enough. The flux of heat from the surface into the thickness of metal is to be 5–10 times more intensive than the flux of heat along the surface of steel which paralyzes the effect. The heat flux along the surface is in inverse proportion with the interval between the strias. Consequently, the power required to observe the effect is determined by $\Delta P > \text{const.}\sqrt{f}$. Practice shows that for the majority of sorts of steel it should be:

$$\Delta P > (1/2)\sqrt{f}\left[\frac{W}{\text{cm}^2}\right]. \qquad (1)$$

Sometimes when preheating steel thoroughly to the temperature 500–600°C it is possible to observe the striated heating effect (1) with lower values of the specific power.

Strias are visible during the time that the superficial layer having the thickness about twice the depth of penetration of currents in heated steel is passing to the non-magnetic modification. Calculation results in

$$t \approx \frac{(0.5/2)10^6}{f} \text{ sec.} \qquad (2)$$

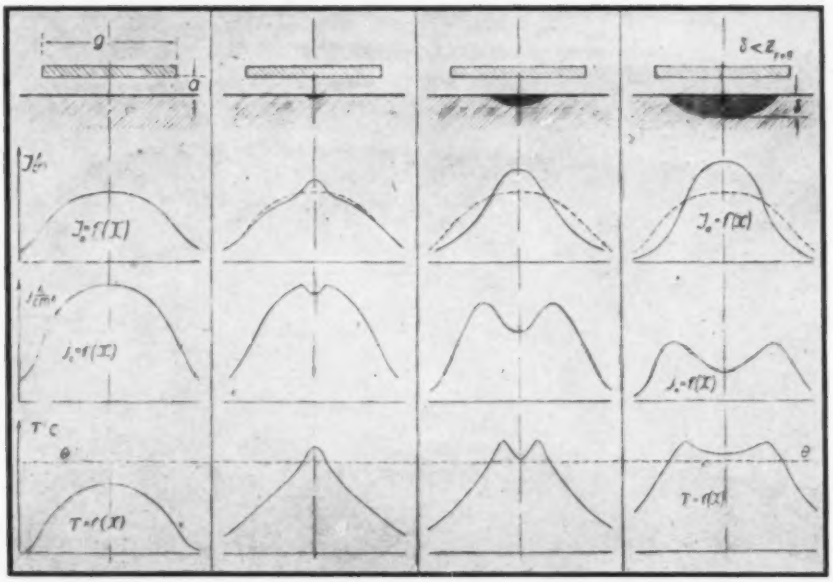

FIG. 5. Distribution of the current I, the current density j, and the temperature T over a steel surface. Vertical hatching indicates zones passed in γ-solution.

Several bright and dark strias may be observed on the surface of steel provided a width no less than 10/20 times the depth of penetration is subjected to simultaneous uniform heating. A "temperature plateau" no less than $[(5/10)/\sqrt{f}]\cdot 10^3$ mm wide should exist on the surface of steel (at the frequency 10^6 c.p.s. the zone of uniform heating should be no less than 5/10 mm).

When the width g of the inductor is less than 5/6 times the depth of penetration of currents in heated steel $Z_{Fe\gamma}$, then only a single bright stria will appear beneath the middle of the inductor. The stria will expand and darken in the middle while the rands will become brighter. In this case the expressions (1) and (2) are no longer applicable; the "life" of strias may be longer or shorter than t.

In Figs. 4 and 5 is shown in separate stages heating for hardening a steel plate with specific power exceeding $2\sqrt{f}W/\text{cm}^2$. It may be seen that the non-uniformity of temperatures observed on the surface of steel is caused not only by the design of the heating coil (the inductor) but also by the properties of the material having the permeability depending upon the temperature.

Uniform heating-up of a surface above the Curie point may occur only with small values of the specific power. With higher power values the wide river of eddy currents will wash out in the surface of narrow steel channels consisting of metal having already lost the magnetic permeability. The homogeneous flow will divide into separate streams and arms.

In Figs. 4 and 5 the columns on the left refer to steel at the temperature below the Curie point. The second and the third columns illustrate separate stages of the formation of the solid solution, the columns of the right—the final moment of heating for hardening.

These columns do not succeed one another in equal time intervals. After the first stria the following ones arise in a quite negligible time lapse. The visual impression is that all strias arise simultaneously. In Fig. 4 these moments are dispersed in order to illustrate how the strias are arising.

The upper row of curves in Figs. 4 and 5 shows the distribution of the current. The dotted line in all these plots is the distribution of the current in a quite homogeneous material (in steel heated altogether above the Curie temperature the distribution of the current is the same as in cold steel).

The zones having passed in γ-solution are shown by vertical hatching.

The second row of curves (j_{0z}) illustrates the distribution of the current density at the surface of steel. The maximum current density does not coincide with the maximum current because the

latter arises in a point where the zone of metal, having lost the magnetic properties, is of the maximal thickness. The periodicity of the curve of the current density is twice the periodicity of the variation of the current.

The lower curves illustrate the distribution of the temperature on the surface of steel. Figure 4 refers to the case when the temperature curve is similar to the current curve. The "fine structure" of striated heating shown in Fig. 5 refers to the case when the temperature curve is similar to the curve of current density.

According to these figures it may be concluded that the higher the specific power applied to steel, the less will be the thickness of the zone of γ-solution attained in the moment when the bright strias will close together.

When it is necessary to harden a width of steel surface of the order of $2000/\sqrt{f}$ mm over a thickness less than $600/\sqrt{f}$ mm, then the correlation of the width and the thickness of the hardened zone will be determined not only by the dimensions of the inductor, but also by the specific power and the heating time. The higher the specific power and the less the heating time, the higher will be the width-to-thickness ratio.

When hardening crankshafts at the frequency 2000 c.p.s. with a small value of the specific power, the heated layer will be of a great thickness but considerably more narrow than the inductor. When it is desirable to obtain a wider layer reaching the cheeks, it is necessary to raise the specific power and to reduce the heating time. Practically it is difficult to obtain at the above frequency the width-to-thickness ratio exceeding 10. So long as $\delta < 600/\sqrt{f}$, the width of the hardened layer will always be less than the width of the inductor.

It is essential to note in this place that in the case when the zone to be heated is narrower than $2000/\sqrt{f}$ mm, the thickness of the layer is smoothly increasing with the heating time. With given specific power, the thickness of the hardened layer may be modified within very wide limits by varying the heating time. This is not true when heating a zone wider than $2000/\sqrt{f}$ mm. In this case γ-solution is building in form of strips which have time to obtain some thickness before closing together. However, the thickness of the layer of γ-solution is not uniform even after the closing together of strias. The final levelling may proceed owing to heat conduction as soon as the thickness of the layer (δ) exceeds $600/\sqrt{f}$ mm.

The "striated heating" effect embraces the appraisement of the distribution of electromagnetic field strength by means of observing visually the heating intensity. When a cylinder of ferromagnetic material is brought into a homogeneous field, its rands will become brightly luminous while the middle part of its lateral surface and the bases will remain cold. In a cylinder of non-magnetic material the rise of temperature on the rands will be considerably less pronounced.

When heating a sphere of ferromagnetic material in a homogeneous field a very bright stria will be visible on the equator of the sphere, although the initial distribution of eddy currents will not have such a pronounced maximum.

The "striated heating" effect may be utilized to make up the judgment upon the readiness of the object for hardening. Provided the heating coil does not envelop the object very closely, it is easy to catch by sight the moment when the dark and the luminous strias on the surface of the object will be washing themselves off and fusing together—this will be the starting point for the whole superficial layer to pass in solid γ-solution. Fixing the moment of vanishing of strias does not require such a skilled eye as the visual determination of temperature. This is even easier than measuring the temperature of an optical pyrometer.

On the Solution of Definite Integrals Occurring in Antenna Theory

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A certain type of definite integrals occurring often in the evaluation of mutual impedance of antennas is solved by the use of differential equations.

IN the evaluation of the mutual impedance of antennas integrals of a certain type often arise. These integrals, up to the present time, had to be evaluated numerically as no analytical expression for them was known.

A number of such integrals occur in a recent paper.[1] All integrals of this particular group are solved by the evaluation of the following integral

$$I=\int_0^h \frac{\exp\left[-j\beta(z^2+r^2)^{\frac{1}{2}}\right]}{(z^2+r^2)^{\frac{1}{2}}}dz. \tag{1}$$

A similar integral,

$$J=\int_0^h \frac{\cos\beta(z^2+l^2)^{\frac{1}{2}}\sin\beta z}{z(z^2+l^2)^{\frac{1}{2}}}dz, \tag{2}$$

has occurred in our work.

The above integrals can be evaluated by the use of differential equations. For example, by substituting

$$z=r\tan\varphi \tag{3}$$

into (1), we have

$$I=\int_0^{\tan^{-1}h/r}\exp(k\sec\varphi)\sec\varphi d\varphi, \tag{4}$$

where $k=-j\beta r$.

Differentiating (4) twice with respect to k under the integral sign, we obtain

$$\frac{dI}{dk}=\int_0^{\tan^{-1}h/r}\exp(k\sec\varphi)\sec^2\varphi d\varphi \tag{5}$$

and

$$\frac{d^2I}{dk^2}=\int_0^{\tan^{-1}h/r}\exp(k\sec\varphi)\sec^3\varphi d\varphi$$

$$=\int_0^{\tan^{-1}h/r}\exp(k\sec\varphi)\times\sec\varphi(1+\tan^2\varphi)d\varphi. \tag{6}$$

[1] Charles W. Harrison, Jr., J. App. Phys. **14**, 306 (1943).

The first term on the right side of (6) is equal to I, our original integral; the second term can be integrated by parts. After making use of (5) we get

$$\frac{d^2I}{dk^2}+\frac{1}{k}\frac{dI}{dk}-I=\frac{h}{kr}\exp\left[\frac{k}{r}(h^2+r^2)^{\frac{1}{2}}\right]. \tag{7}$$

It is interesting to note that the complementary equation

$$\frac{d^2I}{dk^2}+\frac{1}{k}\frac{dI}{dk}-I=0 \tag{8}$$

is the differential equation for the modified Bessel functions.

To obtain a solution for (7) we expand the right side of (7) in a power series:

$$\frac{h}{kr}\exp\left[\frac{k}{r}(h^2+r^2)^{\frac{1}{2}}\right]=\frac{a}{k}\sum_{n=0}^{\infty}\frac{(bk)^n}{n!}, \tag{9}$$

where

$$a=\frac{h}{r}\quad\text{and}\quad b=\frac{(h^2+r^2)^{\frac{1}{2}}}{r}.$$

If we let

$$I=\sum_{m=0}^{\infty}a_mk^m, \tag{10}$$

and substitute (9) and (10) into (7) we can, as a result, obtain the following recurrence relation:

$$a_{m+1}=\frac{1}{(m+1)^2}\left(a_{m-1}+\frac{ab^m}{m!}\right). \tag{11}$$

The subscripts of the coefficient a in Eq. (11) differ by two; hence, we can obtain two independent series, one in even powers of a and one in odd powers of a. The general terms for the coefficients of these two series can be written,

respectively, as

$$a_{2p}=\frac{a_0}{2^{2p}(p!)^2}+\frac{ab}{2^{2p}(p!)^2}\times\sum_{\mu=1}^{p}\frac{[(\mu-1)!]^2(2b)^{2(\mu-1)}}{(2\mu-1)!} \quad (12)$$

and

$$a_{2p+1}=\frac{2^{2p}(p!)^2a}{[(2p+1)!]^2}\left[1+\sum_{\nu=1}^{p}\frac{(2\nu)!}{(\nu!)^2}\left(\frac{b}{2}\right)^{2\nu}\right]. \quad (13)$$

Noting that

$$\sum_{p=0}^{\infty}\frac{k^{2p}}{2^{2p}(p!)^2}=\mathfrak{I}_0(k), \quad (14)$$

where $\mathfrak{I}_0(k)$ is the modified Bessel function, the integral can be written now as

$$I=a_0\mathfrak{I}_0(k)+\sum_{p=1}^{\infty}\frac{ab}{2^{2p}(p!)^2}\times\left[\sum_{\mu=1}^{p}\frac{[(\mu-1)!]^2(2b)^{2(\mu-1)}}{(2\mu-1)!}\right]k^{2p}+\sum_{p=0}^{\infty}\frac{2^{2p}(p!)^2a}{[(2p+1)!]^2}\left[1+\sum_{\nu=1}^{p}\frac{(2\nu)!}{(\nu!)^2}\left(\frac{b}{2}\right)^{2\nu}\right]k^{2p+1}. \quad (15)$$

Equation (15) already contains one of the solutions of the modified Bessel equation (8). As the other solution of (8) is infinite, its coefficient must be zero for the integral I to be finite. Hence (15) represents the complete solution of (7).

To determine the arbitrary constant a_0 we evaluate the integral (4) for $k=0$:

$$I_{k=0}=\int_0^{\tan^{-1}h/r}\sec\varphi\,d\varphi=\frac{1}{2}\ln\frac{(h^2+r^2)^{\frac{1}{2}}+h}{(h^2+r^2)^{\frac{1}{2}}-h}. \quad (16)$$

For $k=0$, Eq. (15) becomes

$$I_{k=0}=a_0, \quad (17)$$

hence

$$a_0=\frac{1}{2}\ln\frac{(h^2+r^2)^{\frac{1}{2}}+h}{(h^2+r^2)^{\frac{1}{2}}-h}, \quad (18)$$

and this value of a_0 can now be substituted in the Eq. (15).

Remembering that $k=-j\beta r$, we have

$$\mathfrak{I}_0(k)=J_0(\beta r) \quad (19)$$

and substituting (19), $k=-j\beta r$ and the values of a and b in Eq. (15) we write now the solution of our integral as

$$I=\frac{1}{2}\ln\frac{(h^2+r^2)^{\frac{1}{2}}+h}{(h^2+r^2)^{\frac{1}{2}}-h}J_0(\beta r)+\frac{h}{4(h^2+r^2)^{\frac{1}{2}}}\sum_{p=1}^{\infty}\frac{(-)^p}{(p!)^2}\left(\frac{\beta r}{2}\right)^{2p}\times\left[\sum_{\mu=1}^{p}\frac{[(\mu-1)!]^2}{(2\mu-1)!}\left(\frac{4(h^2+r^2)}{r^2}\right)^{\mu}\right]+j\beta h\sum_{p=0}^{\infty}(-)^p\left[\frac{p!(2\beta r)^p}{(2p+1)!}\right]^2\times\left[1+\sum_{\nu=1}^{p}\frac{(2\nu)!}{(\nu!)^2}\left(\frac{h^2+r^2}{4r^2}\right)^{\nu}\right]. \quad (20)$$

Integral J, Eq. (2), is solved in a similar manner. The complementary equation of the resulting differential equation is, however, in this case linear with constant coefficients.

The series in Eq. (20) and the corresponding series for J converge very rapidly for antennas of one wave-length or less.

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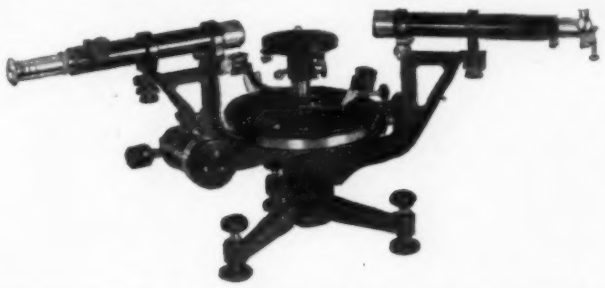

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Recent Applications of Physics

Prepared by CLARK GOODMAN, Associate Editor

Material to be included in this section should be submitted to Dr. Clark Goodman, Massachusetts Institute of Technology, Cambridge 39, Massachusetts.

Electronic Tachometer, Accelerometer, and Vibrometer The adjustment and balancing of gyroscope rotors to conform to the necessarily rigid specifications of airplane instruments require ingenious techniques. C. G. Conn, Ltd., of Elkhart, Indiana has developed an electronic device[1] that rapidly and accurately measures rotational speed, acceleration, and vibration without applying any appreciable load to the rotor. The principles involved are applicable to a wide variety of industrial problems. The tachometer and accelerometer use an electrostatic pick-up consisting of a probe electrode placed near the periphery of the rotor directly adjacent to the gyro vanes. As the rotor revolves, the periodic change in capacitance between the probe and the vanes causes a cyclic redistribution of charge in the grid circuit of a 6SJ7 input tube, which is the first of a two-stage class *A* voltage amplifier. Oscillograms of the voltage obtained show that the voltage varies considerably from one cycle to the next because of minor irregularities in the individual vanes. For this reason, rotational speed cannot be determined accurately from the frequency alone, but is preferably obtained by integrating clipped pulses. This is accomplished with three successive stages: a class *C* limiter, a saturated class *C* square-wave clipper, and a class *B* metering circuit amplifier. The tachometer is calibrated for two ranges of rotational speed, 400 to 1000 r.p.m. and 5000 to 15,000 r.p.m. When used as an accelerometer, generally in testing the deceleration during coasting, the pulses are fed into a differentiating stage and then into a vacuum-tube voltmeter operated at a low plate voltage. A phonograph-type crystal pick-up is used for detecting vibrations. After amplification the output from the crystal actuates a peak-discharge circuit if the rotor needs adjustment. When properly balanced, it is virtually impossible to ascertain by touching the frame or listening to the unit whether the rotor is stationary or revolving.

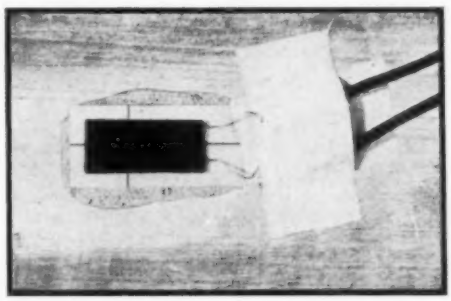
[1] Electronics, p. 100 (June, 1944).

Photoelectric Plethysmograph By passing light through tissue and measuring the opacity with a photo-cell, the state of fullness of blood vessels can be determined. A recording device of this type is known as a photoelectric plethysmograph. Dr. W. E. Gilson of the University of Wisconsin Medical School has recently developed an instrument of this type[1] that uses a direct-coupled push-pull amplifier feeding into a recording milliammeter. The particular study in progress is to measure dilatations of the ear of high altitude fliers, since it has been found that the opacity of the ear is related to the amount of oxygen in the blood. It is also of interest that the method can be used as a measure of blushing in response to certain emotional stimuli.

[1] Electronics, p. 116 (July, 1944).

Magnetic Optical Bench The difficulties of alignment are familiar to anyone who has attempted to set up an optical system in the conventional manner. The procedure has been considerably simplified by the use of a new type of stand which has an Alnico magnet embedded in its base. All that is required is a ferromagnetic surface against which the stand base may be placed. This surface may be a metal-topped table or a sheet of iron mounted on a wall. Two-dimensional adjustment in the plane of the mounting surface is achieved by merely sliding the base by hand. Adjustment perpendicular to the surface is by means of a manually operated clamp.

Stresses and Strains As a result of accelerated production, it has been necessary to develop methods for strain measurement under actual operating conditions. One such device,[1] the resistance-wire-strain gauge, consists of a small grid of one-mil wire supported by paper or plastic and cemented firmly on the spot where strains are to be measured. When stretched or compressed, the wire changes its electrical resistance linearly with the strain. Hence static or dynamic strains up to the highest rates of explosive loading may be measured to a lower limit of about 10^{-6} inch per inch. Such strain gauges are particularly useful for measuring dynamic working loads that cannot be readily calculated, as well as in proving the validity of different assumptions as to the natural periods and modes of vibration. Many measurements of loads in airplane structures during test maneuvers are recorded on multi-element oscillographs. However, in the latest method changes in gauge resistance are used to modulate high frequency radio waves, transmitting to the laboratory oscillograph the strains during a test flight from distances up to 150 miles.



Strain gauge applied to metal strip with Duco cement.

Stresscoat patterns on built-up beryllium-copper bellows.

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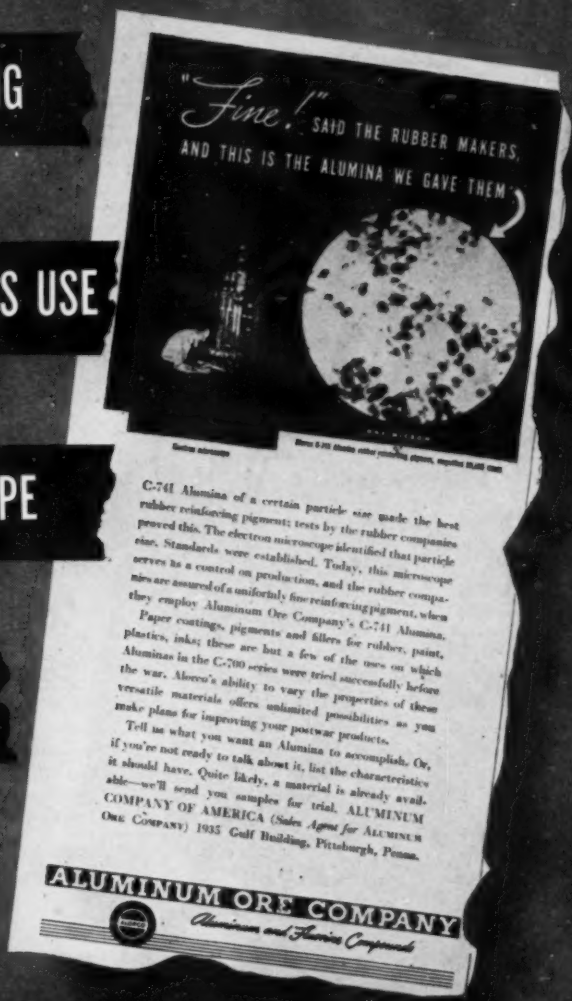
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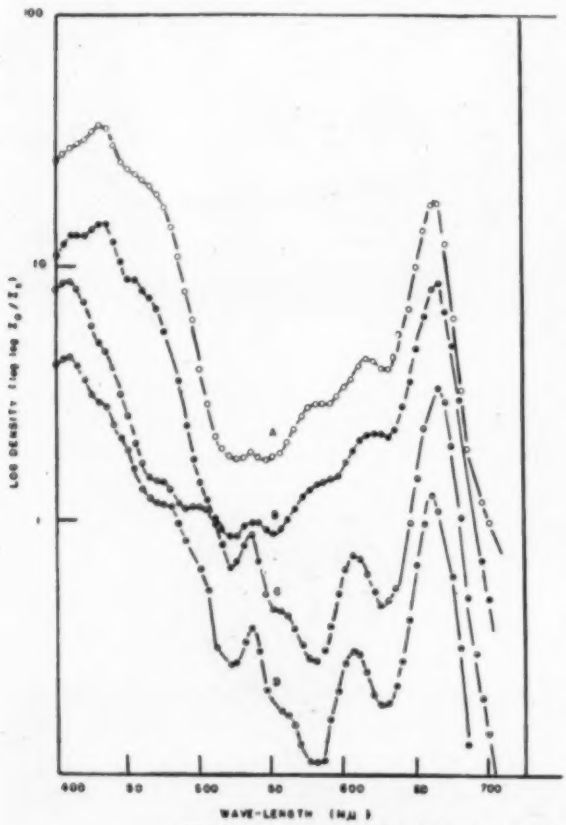
Recent Applications of Physics (continued)

Stresscoat,[2] a limed wood resin dissolved in carbon disulfide, is a brittle lacquer that is widely used for quantitative strain measurements of complex mechanical parts. The surfaces are painted with a thin coating which quickly dries to a brittle film. When the metal part is subjected to an applied stress, the coating forms a series of cracks along the lines of maximum resolved tension. Compression strains may be indicated by applying the test load *before* the coating has dried, and then observing the cracks which result on the release of the load. The sensitivity of the lacquer in each test is determined by a calibrating bar, coated, dried, and loaded at the same time as the test. Full-size parts or models may be used. This method of exploring local strain distribution is usually done in the laboratory after the direction and distribution of the working loads have been measured by means of strain gauges.

[1] A. V. de Forest, Metal Progress, pp. 719–723 (May, 1943).
[2] A. V. de Forest, G. Ellis, and F. B. Stern, Jr., J. App. Mech. **9**, 184 (1942).

Dehydrated Spinach Popeye seems to derive the same energizing effects from spinach regardless of whether it is freshly prepared, canned, or dehydrated. However, a recent study[1] indicates that the nutritional value and palatability of this all-too-familiar vegetable depend upon its treatment. These properties can be correlated with changes in color and pigment content. Thus spectral reflectance measurements from the material or absorption spectra of extracts can be used to indicate the chemical changes during processing and storage of spinach. Such experiments have shown that, in unblanched dehydrated spinach, destruction of chlorophyll is positively correlated with moisture content and is affected very little by the oxygen content of the storage atmosphere. The destruction of carotene is, however, greatly dependent upon oxygen in the storage atmosphere, but is independent of the moisture content of the dried product. The destruction of chlorophyll may be regarded as an indication of loss of palatability and ascorbic acid, but does not indicate loss of carotene. Because changes in chlorophyll obscure color changes owing to carotene content, the latter cannot be correlated with reflectance measurements. The accompanying spectrophotometric curves made on extracts reveal the changes observed for dehydrated spinach stored 32 weeks in air and containing 2 percent moisture (*B*) and 16.3 percent moisture (*C*), as compared with fresh spinach (*A*). The effect of converting this fresh extract of chlorophyll to pheophytin by the addition of oxalic acid is shown in curve *D*. The similarity with curve *C* is apparent.

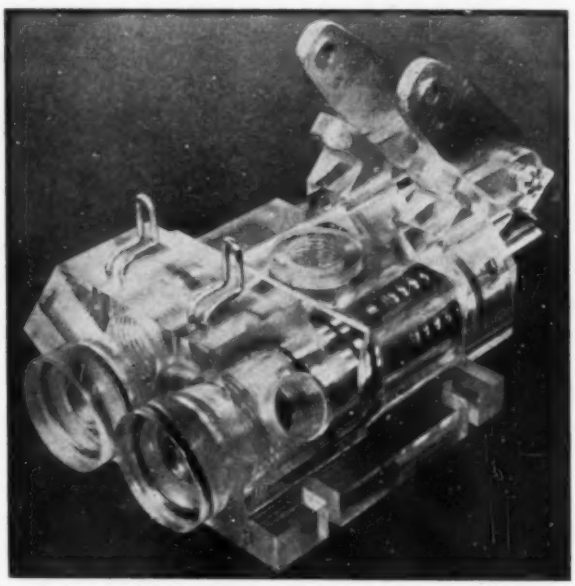


Courtesy of *Industrial and Engineering Chemistry*

Although the importance of chlorophyll to nutrition and to taste and flavor has never been demonstrated, it is labile in nature and in the storage of unblanched dehydrated spinach its conversion to pheophytin may serve as an indication of the state of certain other labile substances important to nutritional value and to quality.

[1] H. J. Dutton, G. F. Bailey, and E. Kobake, Ind. Eng. Chem. **35**, 1173–1177 (1943).

Plastic Models If a photograph is worth a thousand words, a transparent working model of an intricate machine should be worth a thousand photographs. The Ford Motor Company at its Willow Run airplane school has developed a system of teaching with the aid of Plexiglas models, which has yielded astonishing results in increasing efficiency. This method of instruction is being extended throughout the plant with a view to familiarizing workers with the intricate mechanisms that go into the construction of the B-24 Liberators which the company is manufacturing. The accompanying photograph shows a model of a B-24 brake valve. Acrylic plastics are particularly well suited for the manufacture of these models. In addition to their transparency, the ease of machining makes it possible to utilize actual metal parts as inserts. The transparent models offer advantages over the conventional cut-away models in that all parts are intact and the operation is identical with that of actual working conditions. These models also offer promise as an aid in engineering design.



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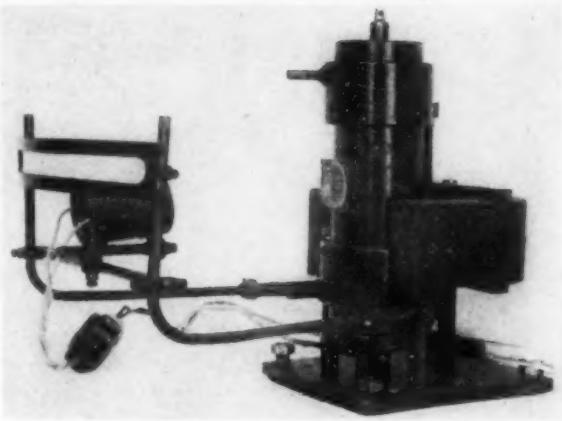

An improved form of the gauge described in Rev. Sci. Inst. **6**, 362 (1935). Indicates vacua from 10^{-6} mm Hg to 6×10^{-4} mm Hg.

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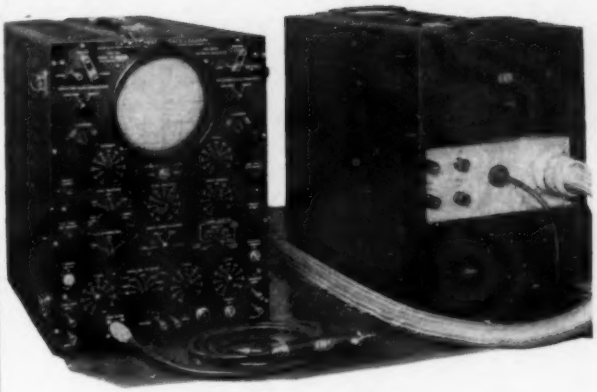

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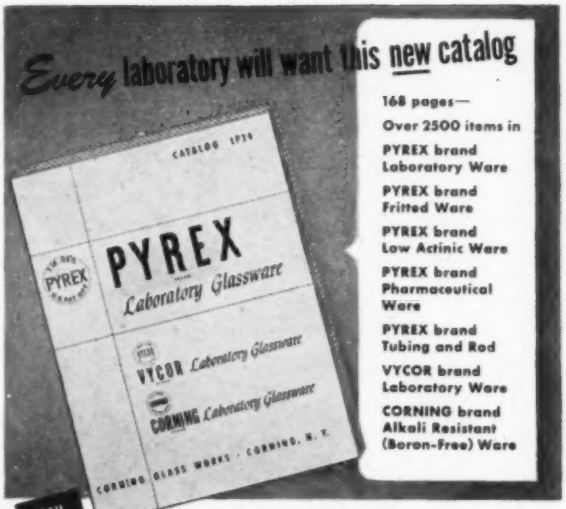
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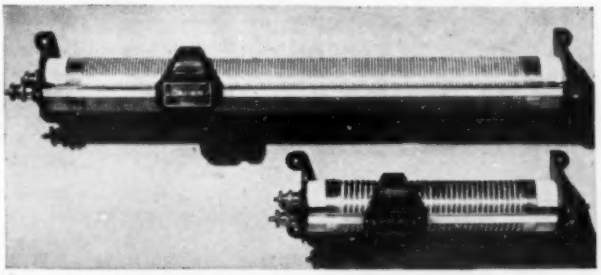

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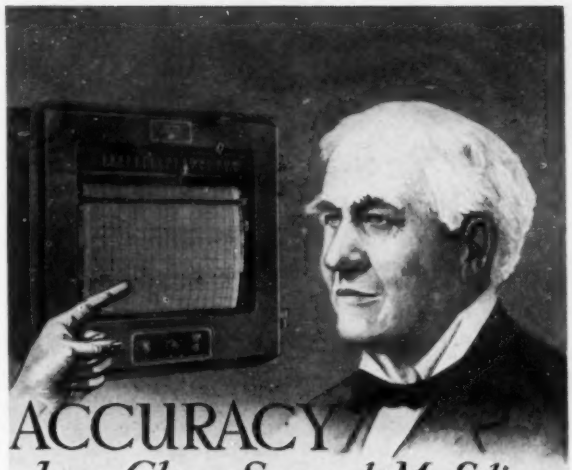

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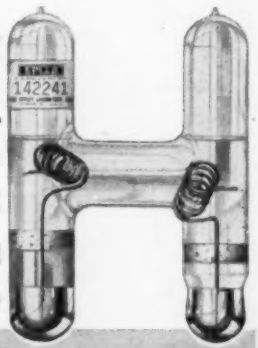

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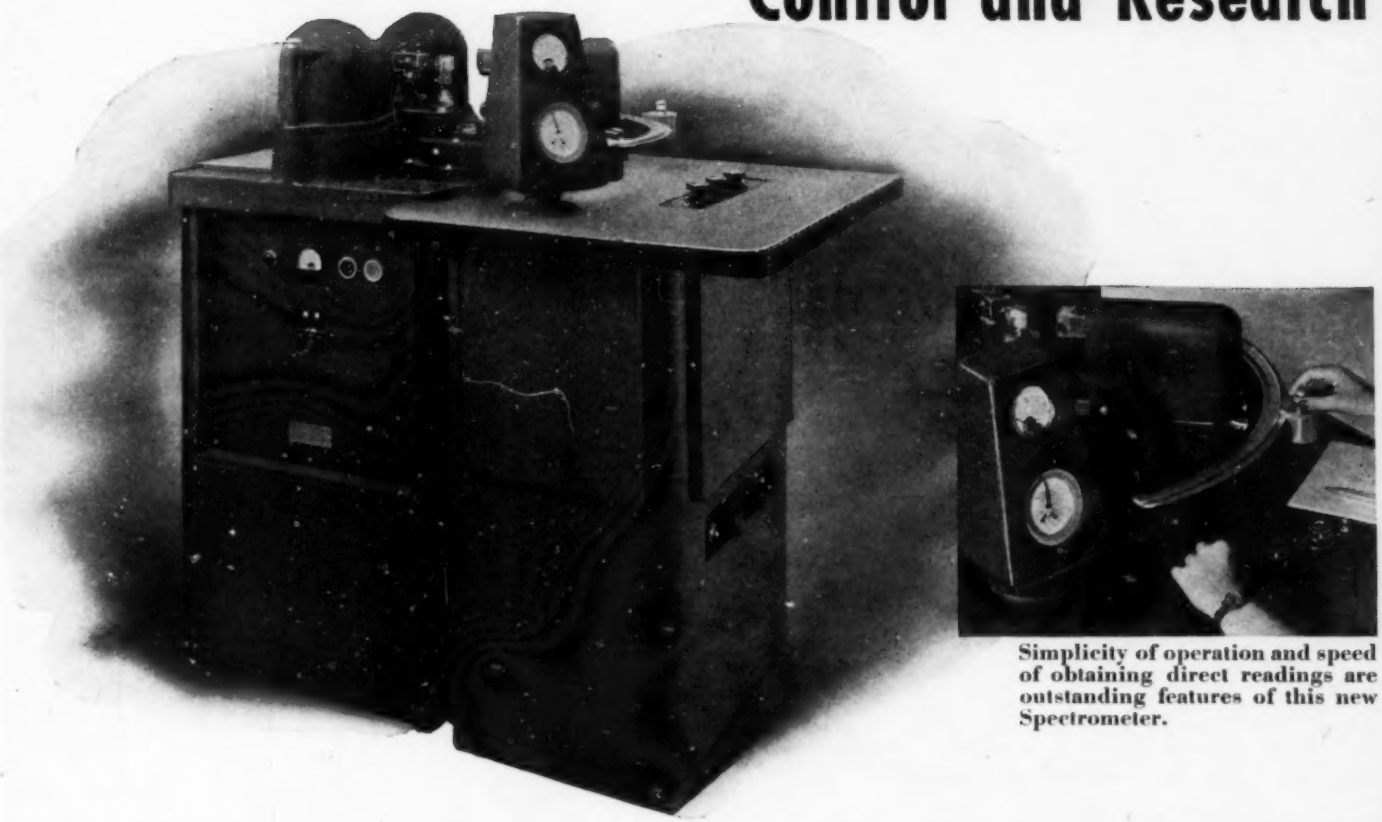

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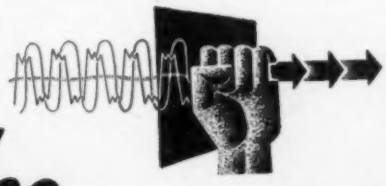

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Gaertner Scientific Corporation — Spectroscopes, Spectrometers, Spectrographs, Spectrophotometers, Heliostats, Measuring Microscopes, Comparators, Cathetometers, Reading Telescopes, Interferometers, Chronographs, Dividing Machines, etc.	xix
General Radio Company — Manufacturers of electronic measuring instruments; vacuum-tube voltmeters, amplifiers and oscillators; wave analyzers, noise meters and analyzers, stroboscopes; laboratory standards of capacitance, inductance and frequency; impedance bridges, decade resistors and condensers; air condensers and variable inductors; rheostats, Variacs, transformers; other laboratory accessories.	ix
Harvey Radio Laboratories, Inc.	xiv
Hewlett-Packard Company — Resistance-Tuned Audio Oscillators; Audio Signal Generators; Harmonic Analyzers; Square Wave Generator; Vacuum Tube Voltmeter; Frequency Standards; Frequency Meters; Automatic Welding Machine Controls.	xi
International Resistance Company — Manufacturers of metallized and wirewound fixed and variable Resistors including high voltage and high frequency types.	iii
Leeds & Northrup Company — Manufacturers of Galvanometers, Resistors, Bridges, Condensers, Inductances, Potentiometers, Testing Sets; Temperature Measuring, Recording, and Controlling Apparatus; Instruments for Measuring and Controlling Conductivity of Electrolytes and Hydrogen Ion Concentrations.	i

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Machlett Laboratories, Incorporated — X-ray tubes for medical, industrial and scientific uses; high voltage rectifying valves for x-ray apparatus; special electronic tubes.	xv
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North American Philips Company, Inc. — Manufacturers of Searchray (X-Ray) Apparatus; X-Ray Diffraction Apparatus; Electronic Measuring Instruments; Direct Reading Frequency Meters; High Frequency Heating Equipment; Tungsten and Molybdenum in powder, rod, wire and sheet form; Fine Wire; Diamond Dies.	xxvii
Perkin-Elmer Corporation — Manufacturers of custom built optical instruments; prisms, lenses and mirrors in all materials including: Glass, Quartz, Fluorite, Lithium Fluoride, Sodium Chloride, Potassium Bromide, Calcite; Optical Flats, Plane Parallels, Interferometer Plates, Retardation Plates.	vii
RCA Manufacturing Company, Inc. — RCA Oscillators and Oscillographs, RCA Test Equipment, RCA Ultra-Sensitive DC Meter.	xxi
Rubicon Company — Galvanometers, electrometers, potentiometers, Wheatstone and Kelvin bridges, resistance boxes, hydrogen ion and conductivity apparatus.	xxv
Shallcross Mfg. Company — Taylor High Voltage Resistors, Kilovoltmeters, Megohm Decade Resistance Boxes, Bridges, Resistance Standards, Test Sets, Attenuators, and other laboratory apparatus. Solid silver contact rotary selector switches, Super Akra-ohm, non-reactive wirewound resistors. Special apparatus built to specifications.	xii
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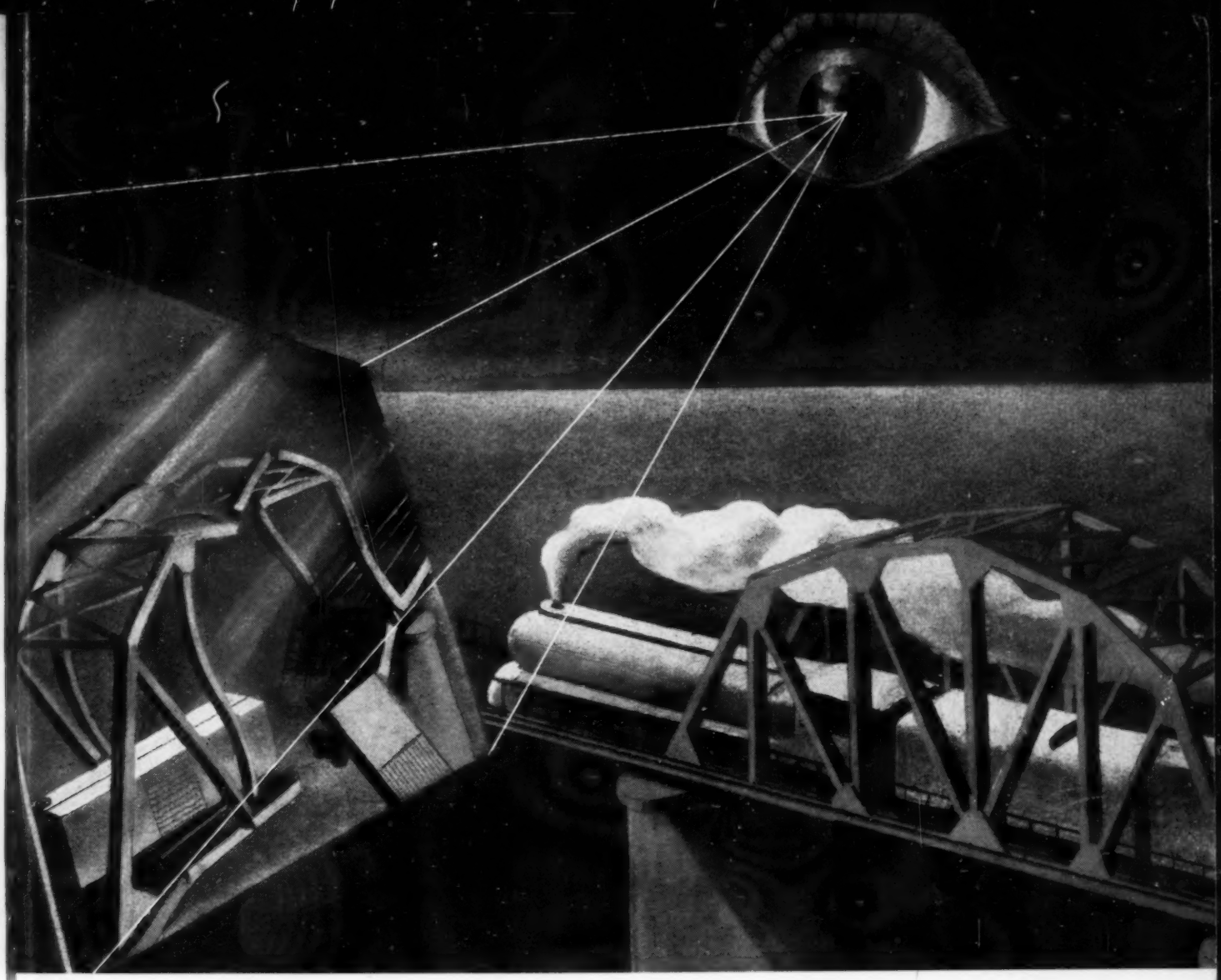

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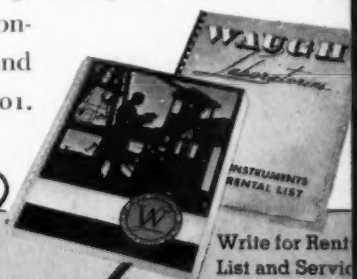

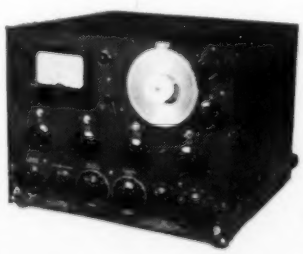

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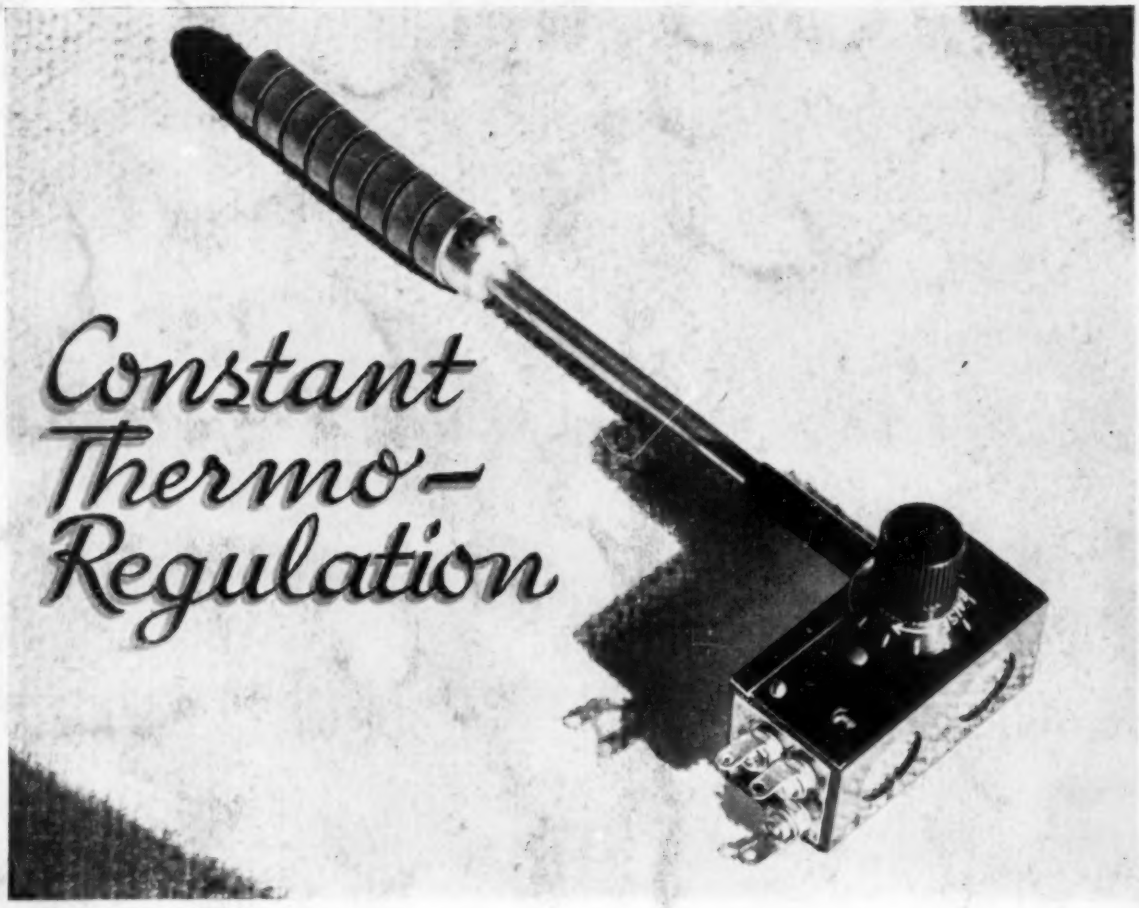

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